Cascadia Great Earthquakes from Paleoseismic data: A progress Report on Marine, Lacustrine and Onshore Evidence Moving toward Paleo-Slip Models

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Most Recent Publications

Goldfinger, C., Nelson, C.H., Morey, A., Johnson, J.E., Gutierrez-Pastor, J., Eriksson, A.T., Karabanov, E., Patton, J., Gracia, E., Enkin, R., Dallimore, A., Dunhill, G., and Vallier, T., 2012, ***Turbidite Event History: Methods and Implications for Holocene Paleoseismicity of the Cascadia Subduction Zone***, USGS Professional Paper 1661-F, Reston, VA, U.S. Geological Survey, p. 362 p, 64 Figures. In press. Unformatted preprint available at http://pubs.usgs.gov/pp/pp1661f/

Publications in Press

Goldfinger, C., Morey, A., Black, B., and Patton, J., 2012 in revision, ***Spatially Limited Mud Turbidites on the Cascadia Margin: Segmented Earthquake Ruptures?,*** *in* Pantosti, D., Gracia, E., Lamarche, G., Nelson, C.H., and Tinti, S., eds., Research Conference Submarine Paleoseismology: The Offshore Search of Large Holocene Earthquakes: Obergurgl, Austria, Natural Hazards and Earth System Science.

Morey, A.E., Goldfinger, C., Briles, C.E., Gavin, D.G., Colombaroli, D., Kusler, J.E., 2012, in revision, ***Potential Lacustrine Records of Cascadia Great Earthquakes***, *in* Pantosti, D., Gracia, E., Lamarche, G., Nelson, C.H., and Tinti, S., eds., Research Conference Submarine Paleoseismology: The Offshore Search of Large Holocene Earthquakes: Obergurgl, Austria, Natural Hazards and Earth System Science.

Goldfinger, C., Ikeda, Y., and Yeats, R.S., 2011 submitted, ***Superquakes and Supercycles***. Seismological Research Letters.

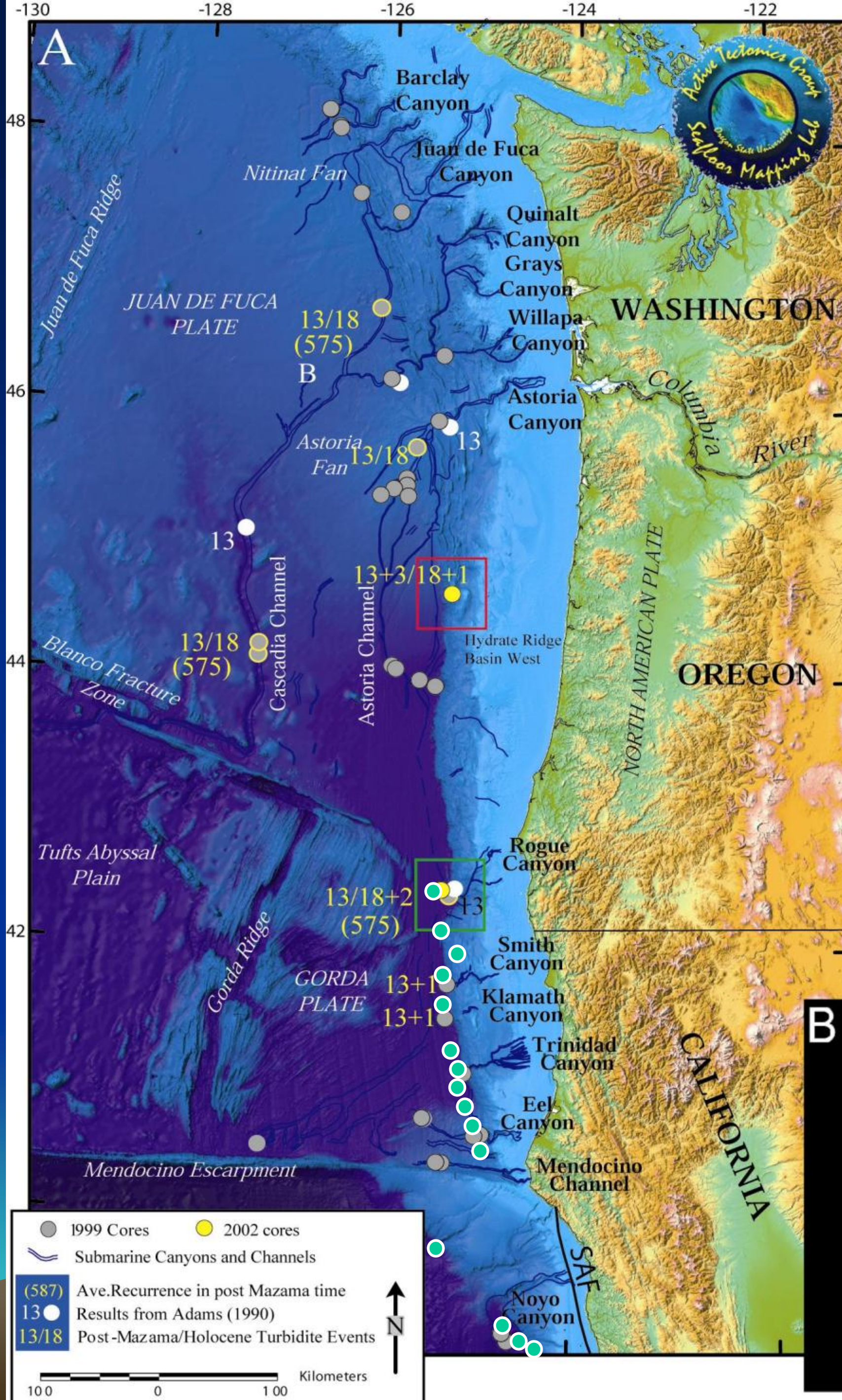
In Cascadia, onshore and offshore paleoseismology have revealed a long history of great earthquakes.

We set out in 1999 to prove the turbidite story wrong, and failed.

Cascadia Turbidite Paleoseismology based on event correlation along strike.

1) Aerial extent
2) Synchroneity, and
3) Sedimentology.

Stratigraphic correlation, tests of synchronous triggering, and 14C ages have led to a credible (we think) record of 43 events of variable size and strike length during the Holocene.



Turbidite Paleoseismology:

Extending the earthquake record

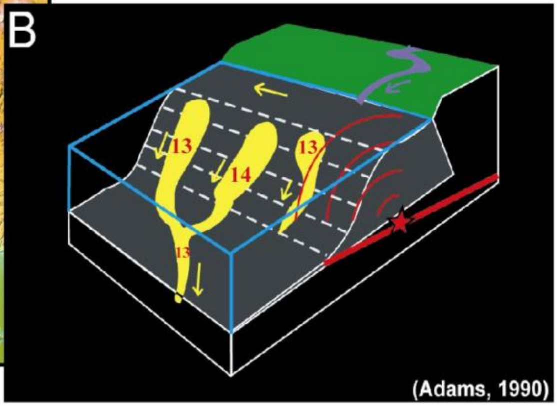
Cascadia Core Sites:

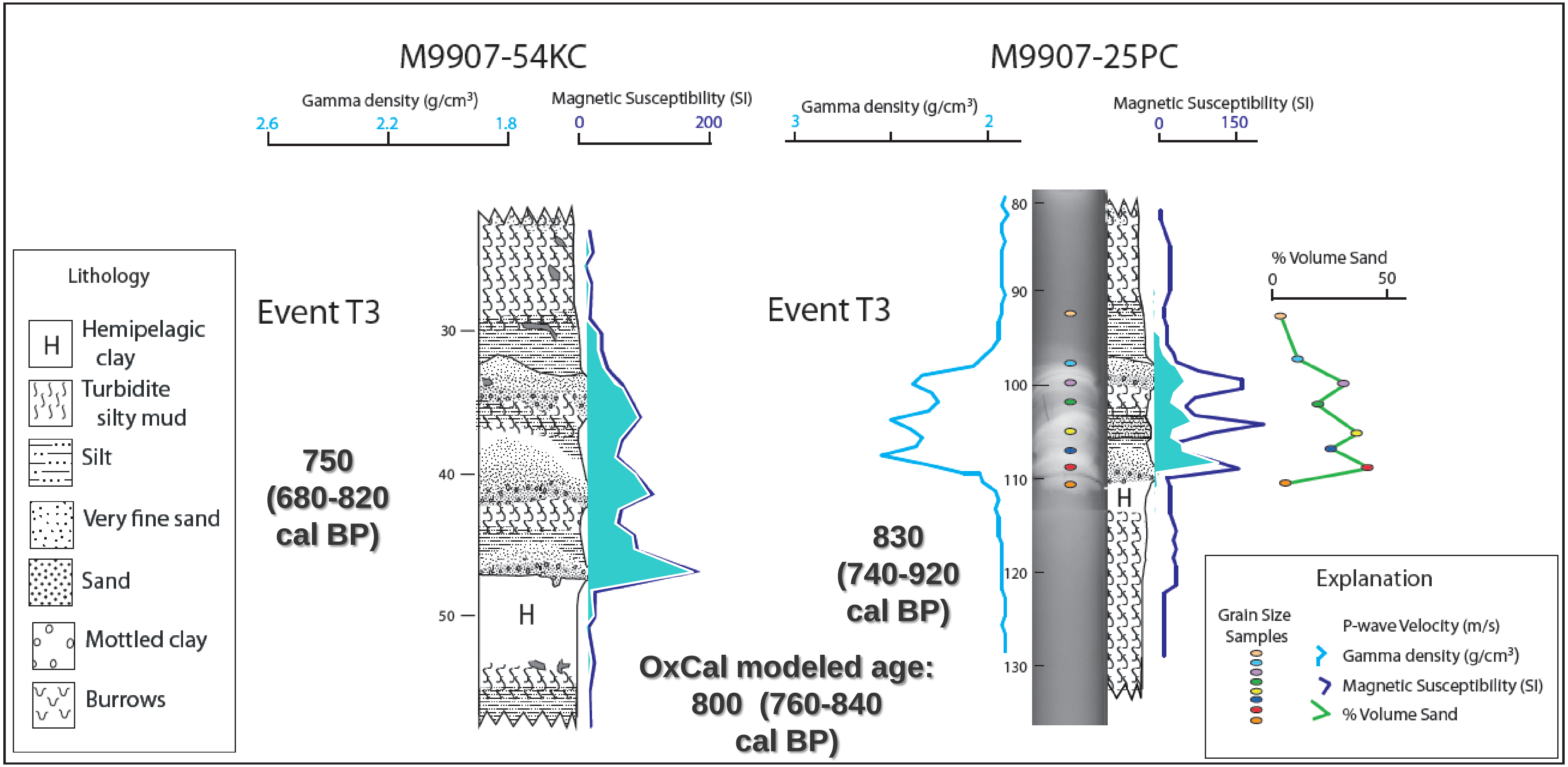
1999 = gray

2002 = yellow

2009 = green

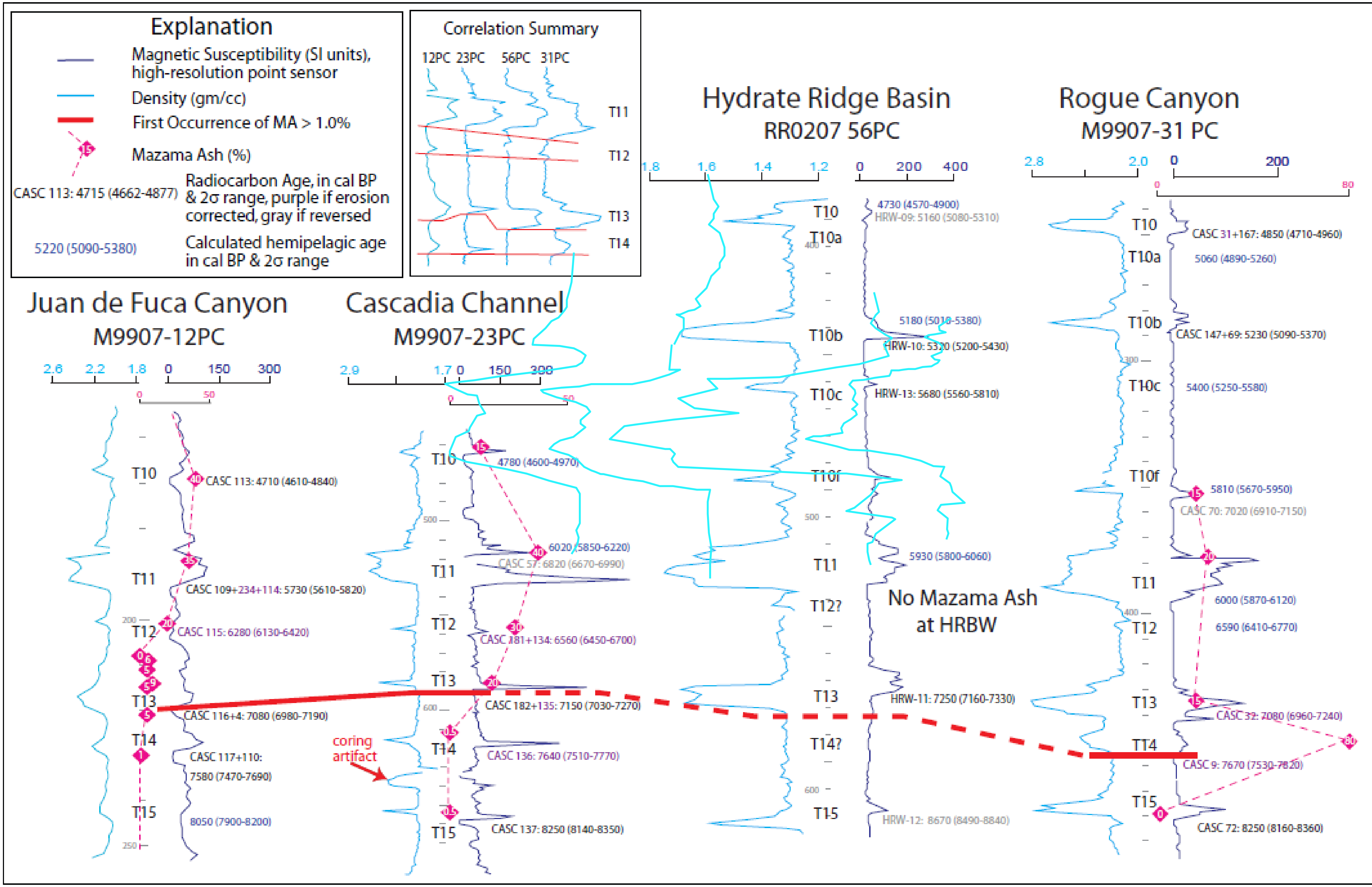
Selected older existing cores = white





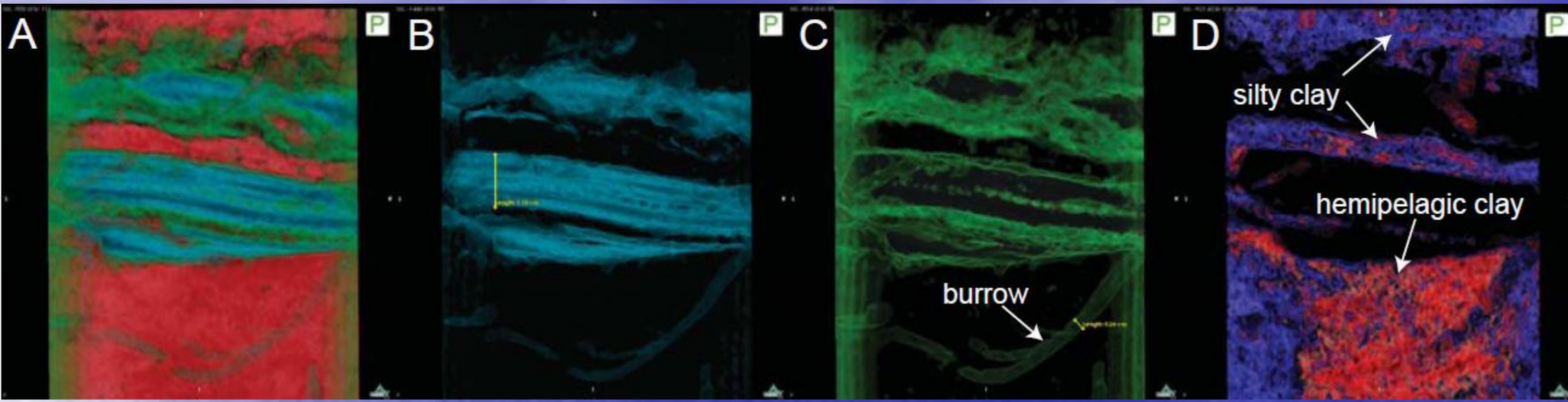
Subsurface correlation 101. Techniques developed and used mostly by the oil industry since 1920.

Looking closely, the main structure of these turbidites is a series of fining upward "pulses" (Bouma A-C) capped by a fining upward tail. The multiple structure is commonly maintained through channel confluences, and between isolated sites as shown by this example from two cores 300 km apart, with source areas 420-500 km apart. These channels never meet.



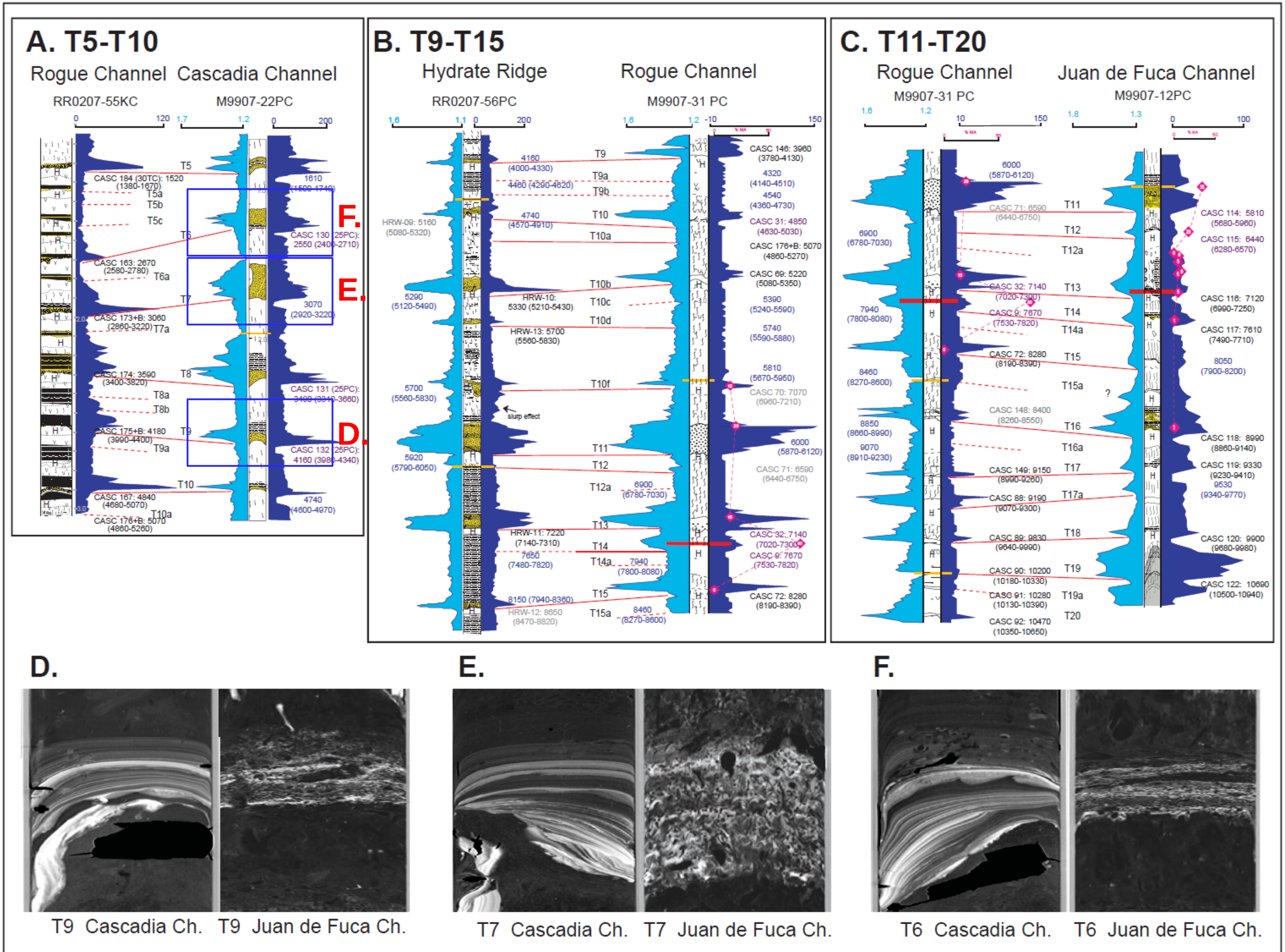
Explanation
Magnetic Susceptibility (SI units), high-resolution point sensor
Density (gm/cc)
First Occurrence of MA > 1.0%
Mazama Ash (%)
CASC 113: 4715 (4662-4877)
Radiocarbon Age, in cal BP & 2σ range, purple if erosion corrected, gray if reversed
5220 (5090-5380)
Calculated hemipelagic age in cal BP & 2σ range
Correlation Summary
12PC 23PC 56PC 31PC
T11
T12
T13
T14
Juan de Fuca Canyon
M9907-12PC
Cascadia Channel
M9907-23PC
Hydrate Ridge Basin
RR0207 56PC
Rogue Canyon
M9907-31 PC
CASC 113: 4710 (4610-4840)
CASC 109+234+114: 5730 (5610-5820)
CASC 115: 6280 (6130-6420)
CASC 116+4: 7080 (6980-7190)
CASC 117+110: 7580 (7470-7690)
8050 (7900-8200)
coring artifact
4780 (4600-4970)
6020 (5850-6220)
CASC 57: 6820 (6670-6990)
CASC 181+134: 6560 (6450-6700)
CASC 182+135: 7150 (7030-7270)
CASC 136: 7640 (7510-7770)
CASC 137: 8250 (8140-8350)
4730 (4570-4900)
HRW-09: 5160 (5080-5310)
5180 (5010-5380)
HRW-10: 5320 (5200-5430)
HRW-13: 5680 (5560-5810)
5930 (5800-6060)
No Mazama Ash at HRBW
HRW-11: 7250 (7160-7330)
HRW-12: 8670 (8490-8840)
T10
T10a
T10b
T10c
T10f
T11
T12?
T12
T13
T14?
T14
T15
CASC 31+167: 4850 (4710-4960)
5060 (4890-5260)
CASC 147+69: 5230 (5090-5370)
5400 (5250-5580)
5810 (5670-5950)
CASC 70: 7020 (6910-7150)
6000 (5870-6120)
6590 (6410-6770)
CASC 32: 7080 (6960-7240)
CASC 9: 7670 (7530-7820)
CASC 72: 8250 (8160-8360)

Turbidite regional fingerprints based on their structure: Multiple fining upward sequences.

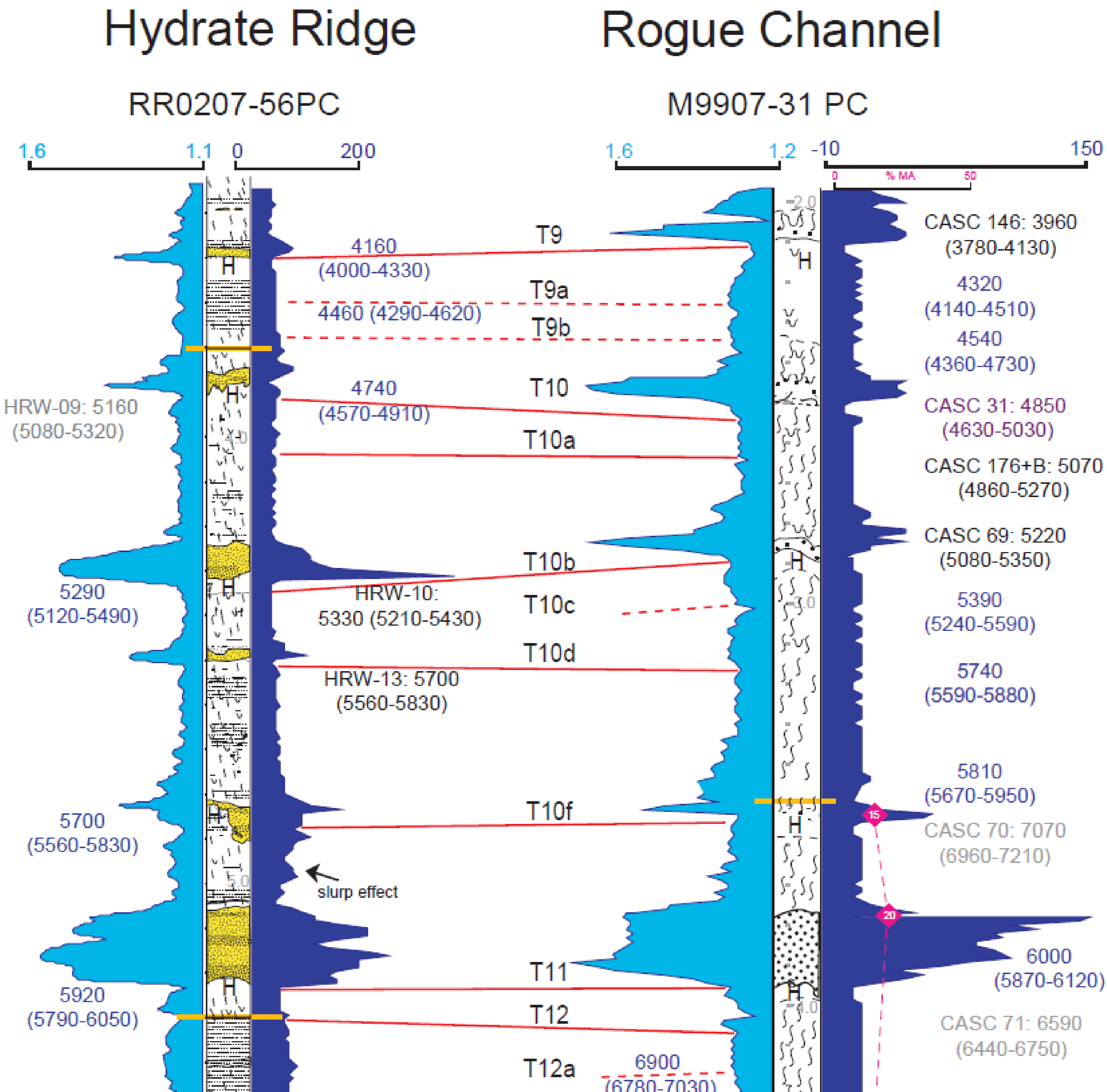


CT imagery is invaluable for understanding turbidite structure and defining stratigraphic boundaries in detail. This image breaks out the sand fraction, the silt fraction, and the hemipelagic clay by their respective CT density values.

The CT can reveal such subtle features as a worm burrow which is lined with material slightly more dense than its surroundings (biogenic clay)



A. T5-T10
Rogue Channel
Cascadia Channel
RR0207-55KC
M9907-22PC
T5
T5a
T5b
T5c
T6
T6a
T7
T7a
T8
T8a
T8b
T9
T9a
T10
T10a
CASC 184 (30TC): 1520 (1380-1670)
CASC 163: 2670 (2580-2780)
CASC 173+B: 3060 (2860-3220)
CASC 174: 3590 (3400-3820)
CASC 175+B: 4180 (3990-4400)
CASC 167: 4840 (4680-5070)
CASC 176+B: 5070 (4860-5260)
1610 (1500-1740)
CASC 130 (25PC): 2550 (2400-2710)
3070 (2920-3220)
CASC 131 (25PC): 3490 (3340-3660)
CASC 132 (25PC): 4160 (3980-4340)
4740 (4600-4970)
F.
E.
D.
B. T9-T15
Hydrate Ridge
Rogue Channel
RR0207-56PC
M9907-31 PC
HRW-09: 5160 (5080-5320)
5290 (5120-5490)
5700 (5560-5830)
5920 (5790-6050)
4160 (4000-4330)
4460 (4290-4620)
4740 (4570-4910)
HRW-10: 5330 (5210-5430)
HRW-13: 5700 (5560-5830)
slurp effect
HRW-11: 7220 (7140-7310)
7650 (7480-7820)
8150 (7940-8360)
HRW-12: 8650 (8470-8820)
T9
T9a
T9b
T10
T10a
T10b
T10c
T10d
T10f
T11
T12
T12a
T13
T14
T14a
T15
T15a
6900 (6780-7030)
7940 (7800-8080)
8460 (8270-8600)
CASC 146: 3960 (3780-4130)
4320 (4140-4510)
4540 (4360-4730)
CASC 31: 4850 (4630-5030)
CASC 176+B: 5070 (4860-5270)
CASC 69: 5220 (5080-5350)
5390 (5240-5590)
5740 (5590-5880)
5810 (5670-5950)
CASC 70: 7070 (6960-7210)
6000 (5870-6120)
CASC 71: 6590 (6440-6750)
CASC 32: 7140 (7020-7300)
CASC 9: 7670 (7530-7820)
CASC 72: 8280 (8190-8390)
C. T11-T20
Rogue Channel
Juan de Fuca Channel
M9907-31 PC
M9907-12PC
6000 (5870-6120)
CASC 71: 6590 (6440-6750)
6900 (6780-7030)
7940 (7800-8080)
8460 (8270-8600)
8850 (8660-8990)
9070 (8910-9230)
CASC 32: 7140 (7020-7300)
CASC 9: 7670 (7530-7820)
CASC 72: 8280 (8190-8390)
CASC 148: 8400 (8260-8550)
CASC 149: 9150 (8990-9260)
CASC 88: 9190 (9070-9300)
CASC 89: 9830 (9640-9990)
CASC 90: 10200 (10180-10330)
CASC 91: 10280 (10130-10390)
CASC 92: 10470 (10350-10650)
T11
T12
T12a
T13
T14
T14a
T15
T15a
T16
T16a
T17
T17a
T18
T19
T19a
T20
CASC 114: 5810 (5680-5960)
CASC 115: 6440 (6280-6570)
CASC 116: 7120 (6990-7250)
CASC 117: 7610 (7490-7710)
8050 (7900-8200)
CASC 118: 8990 (8860-9140)
CASC 119: 9330 (9230-9410)
9530 (9340-9770)
CASC 120: 9900 (9680-9980)
CASC 122: 10690 (10500-10940)
D.
E.
F.
T9 Cascadia Ch.
T9 Juan de Fuca Ch.
T7 Cascadia Ch.
T7 Juan de Fuca Ch.
T6 Cascadia Ch.
T6 Juan de Fuca Ch.



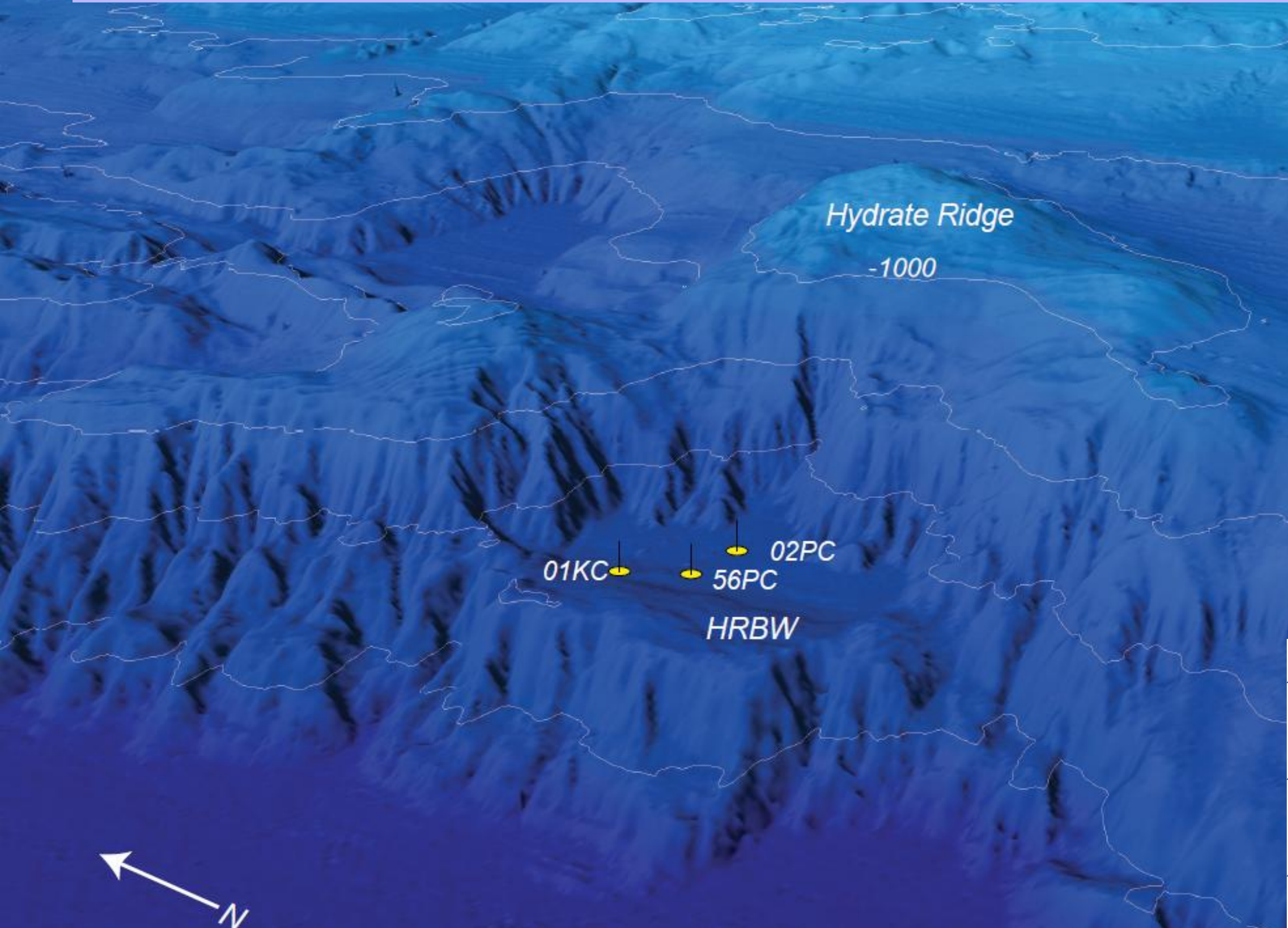
Ages and ranges are of three types:

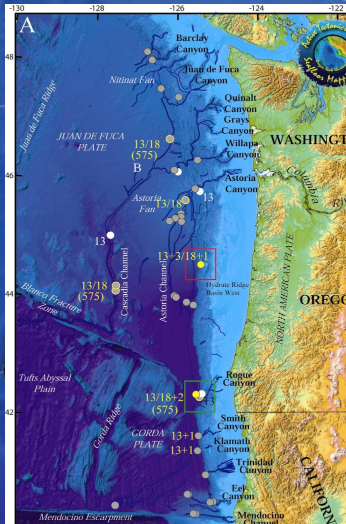
1. **Conventional ages**
2. **Erosion corrected ages**
3. **Benthic foram ages (not common)**

All ages require corrections for sample thickness, and a time and space variant reservoir correction. Some ages are also corrected for differential basal erosion, which is apparent in some cases though multiple cores

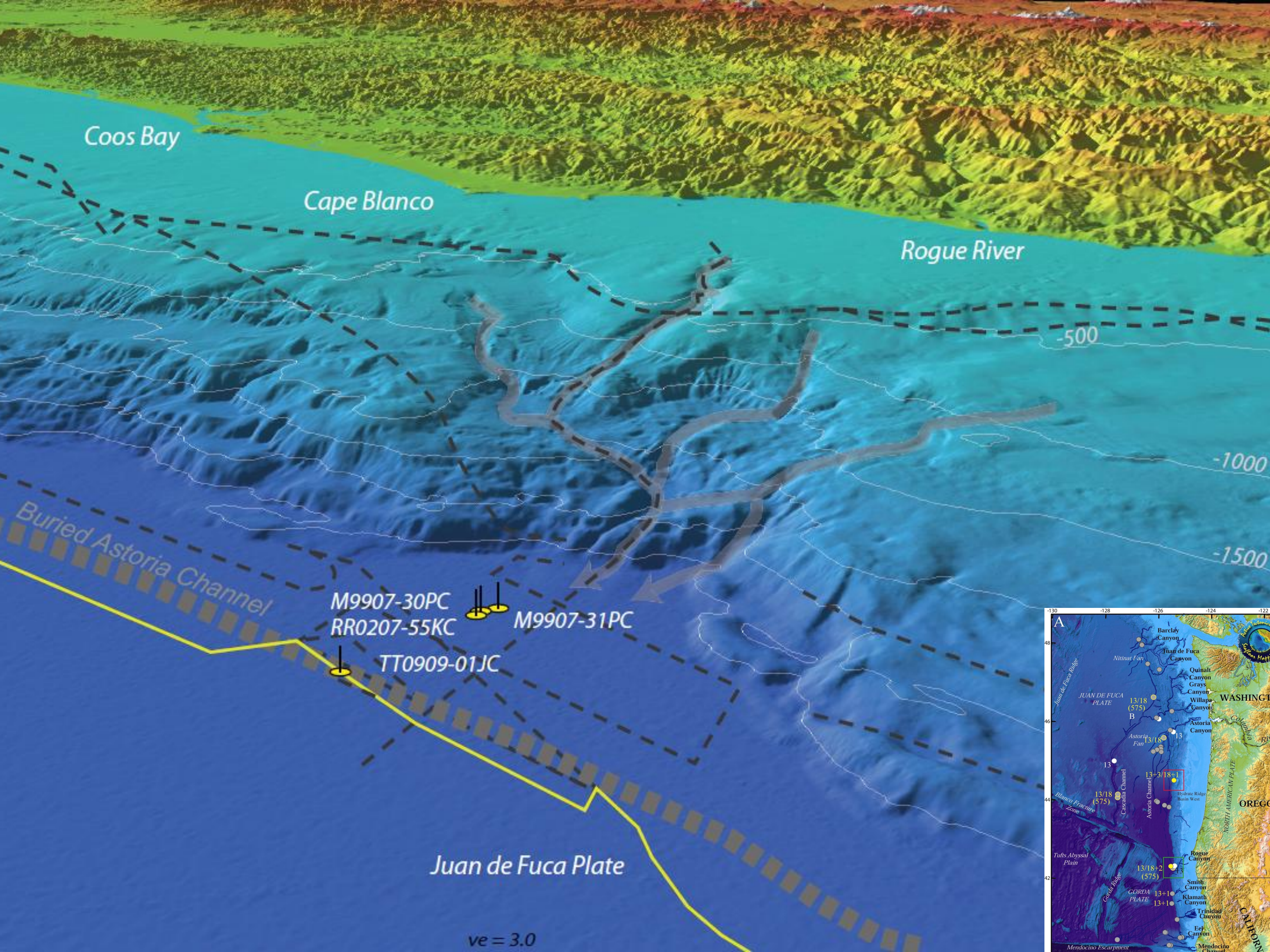
All error ranges, whether calculated or estimated are propagated using sum of squares methods.

In addition to ~ 19 turbidites that appear to correlate along much of the margin (though with variable northern and southern limits), there are additional thinner events found almost exclusively along the southern margin south of Hydrate Ridge (44.5N).



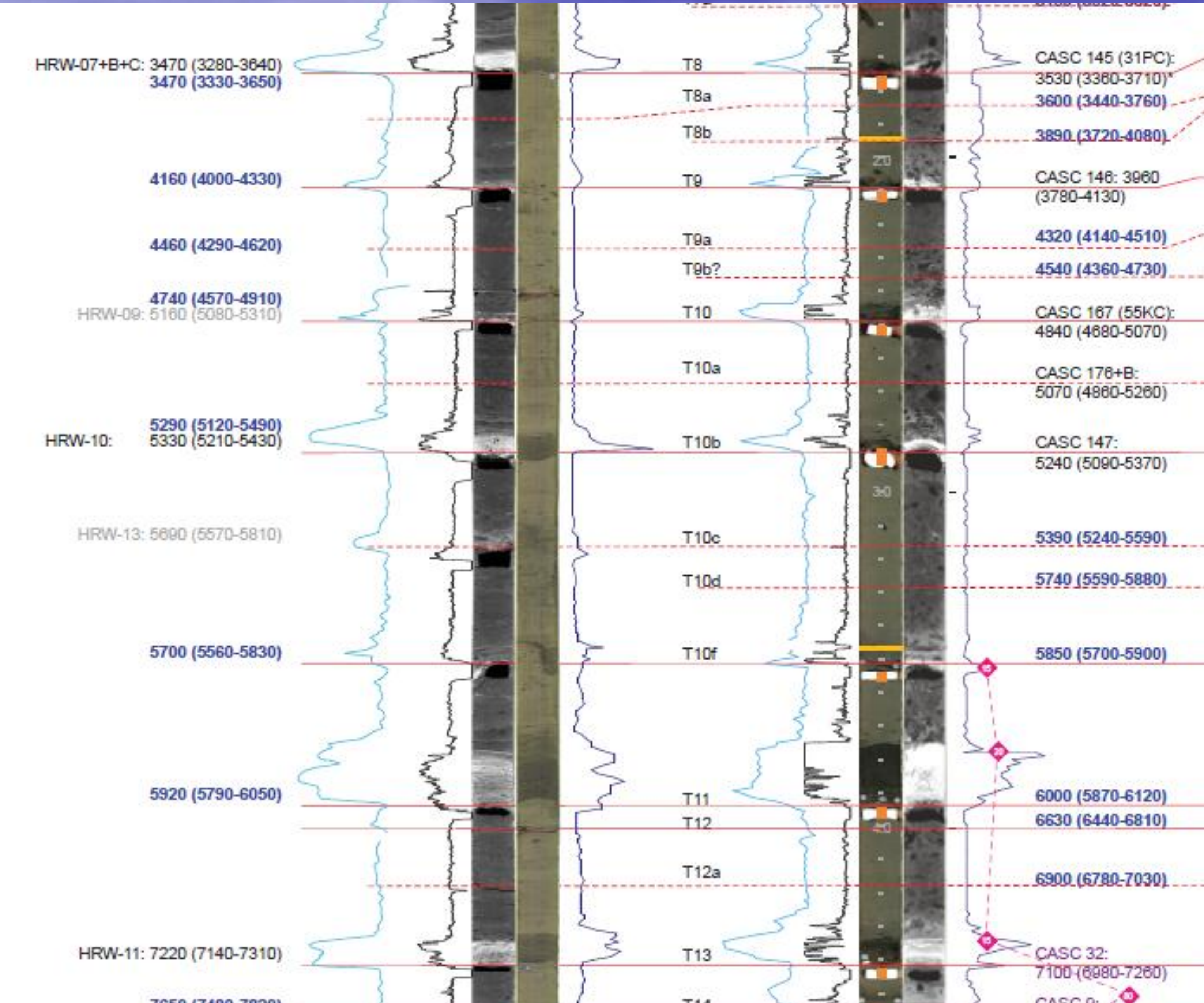


<u>Hydrate Ridge basin is isolated, and cannot receive input from terrestrial sources or storm/tsunami wave disturbance.</u>


Coos Bay
Cape Blanco
Rogue River
-500
-1000
-1500
Buried Astoria Channel
M9907-30PC
RR0207-55KC
M9907-31PC
TT0909-01JC
Juan de Fuca Plate
ve = 3.0
A
Barclay Canyon
Juan de Fuca Canyon
Nitinat Fan
Quinalt Canyon
Grays Canyon
Willapa Canyon
Astoria Canyon
WASHINGT
JUAN DE FUCA PLATE
Juan de Fuca Ridge
13/18 (575)
B
Astoria Fan
13
13/18
13+3/18+1
Hydrate Ridge Basin West
Cascadia Channel
Astoria Channel
Blanco Fracture Zone
NORTH AMERICAN PLATE
OREGO
Tufts Abyssal Plain
Gorda Ridge
GORDA PLATE
Rogue Canyon
13/18+2 (575)
Smith Canyon
13+1
Klamath Canyon
Trinidad Canyon
Eel Canyon
Mendocino Escarpment
Mendocino Channel
-130
-128
-126
-124
-122
48
46
44
42

Hydrate Ridge Basin West

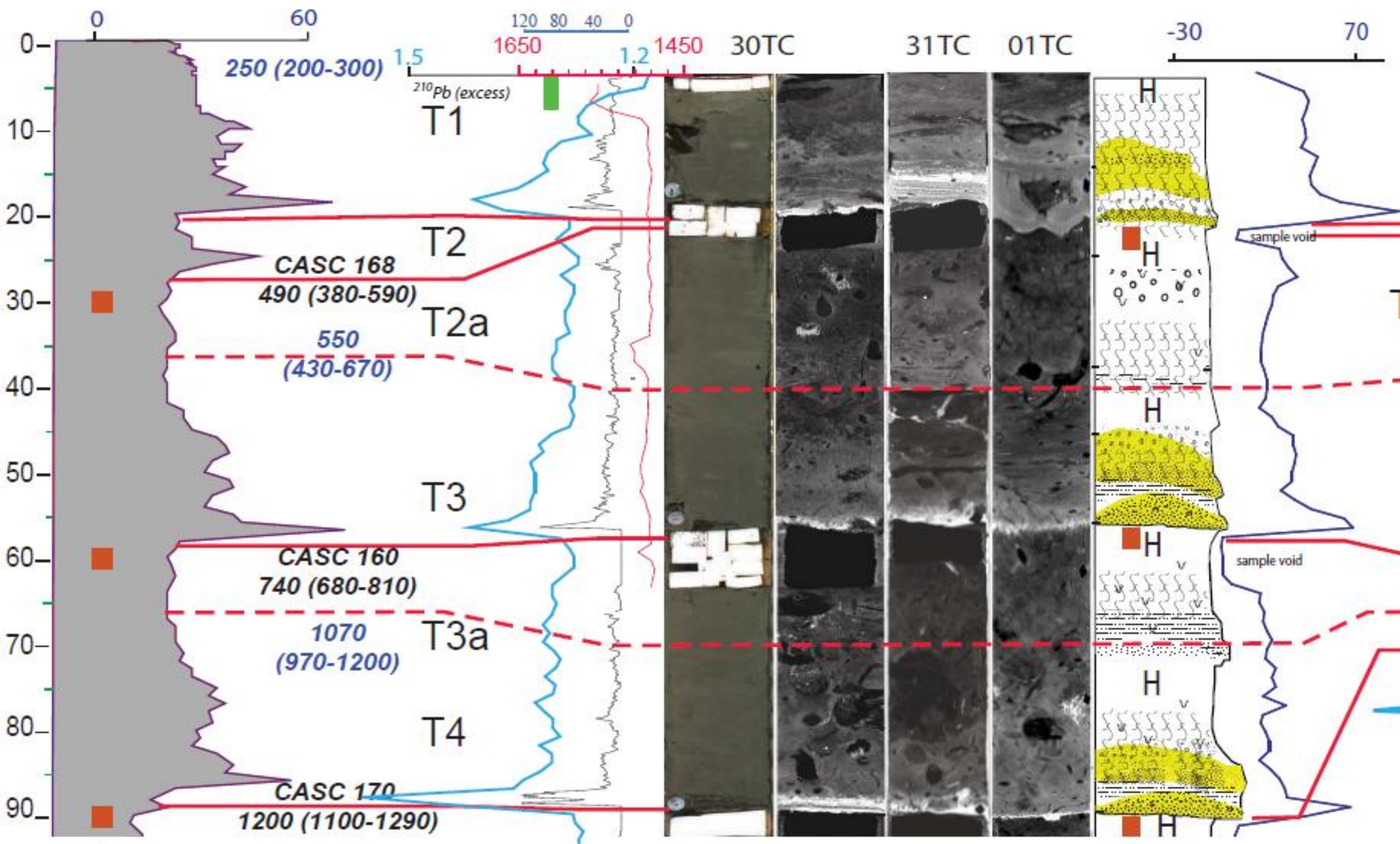
Rogue Apron



Zooming in…

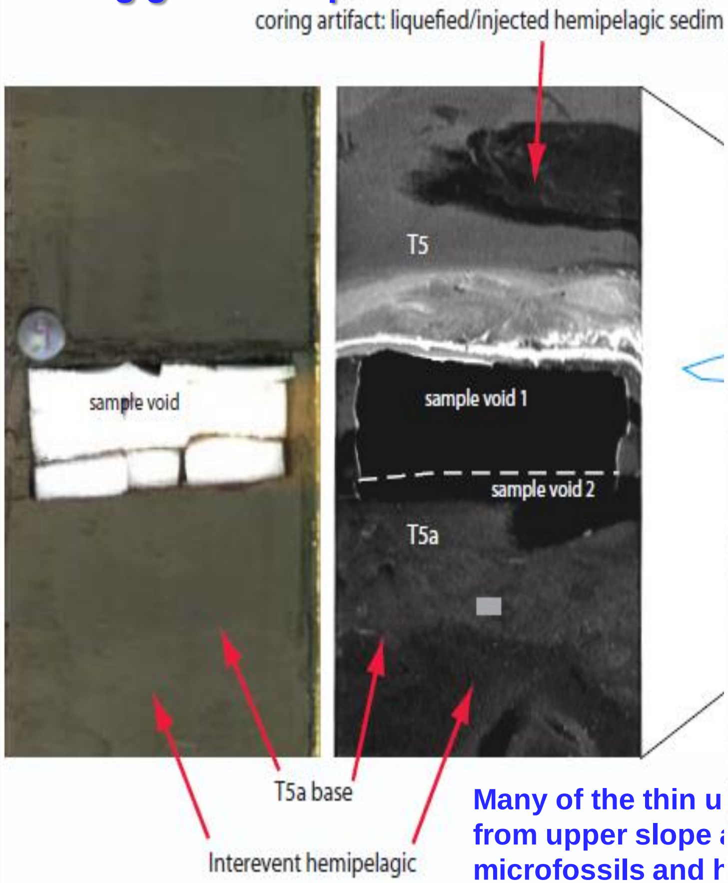
middle Holocene

Southern margin mud-slit turbidites are apparent in geophysical logs, CT imagery, and sedimentological examination

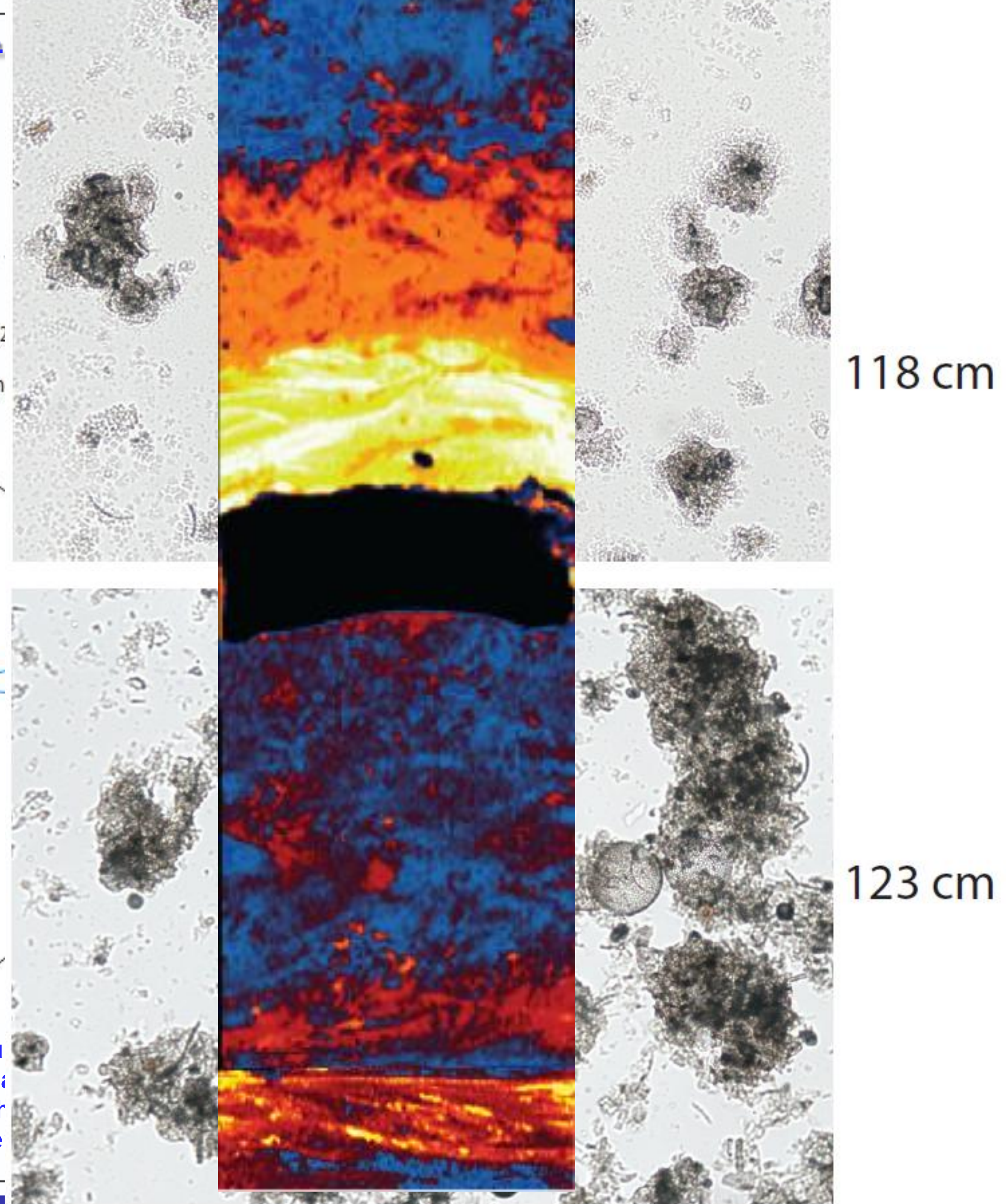


The spatially limited southern turbidites, what are they?

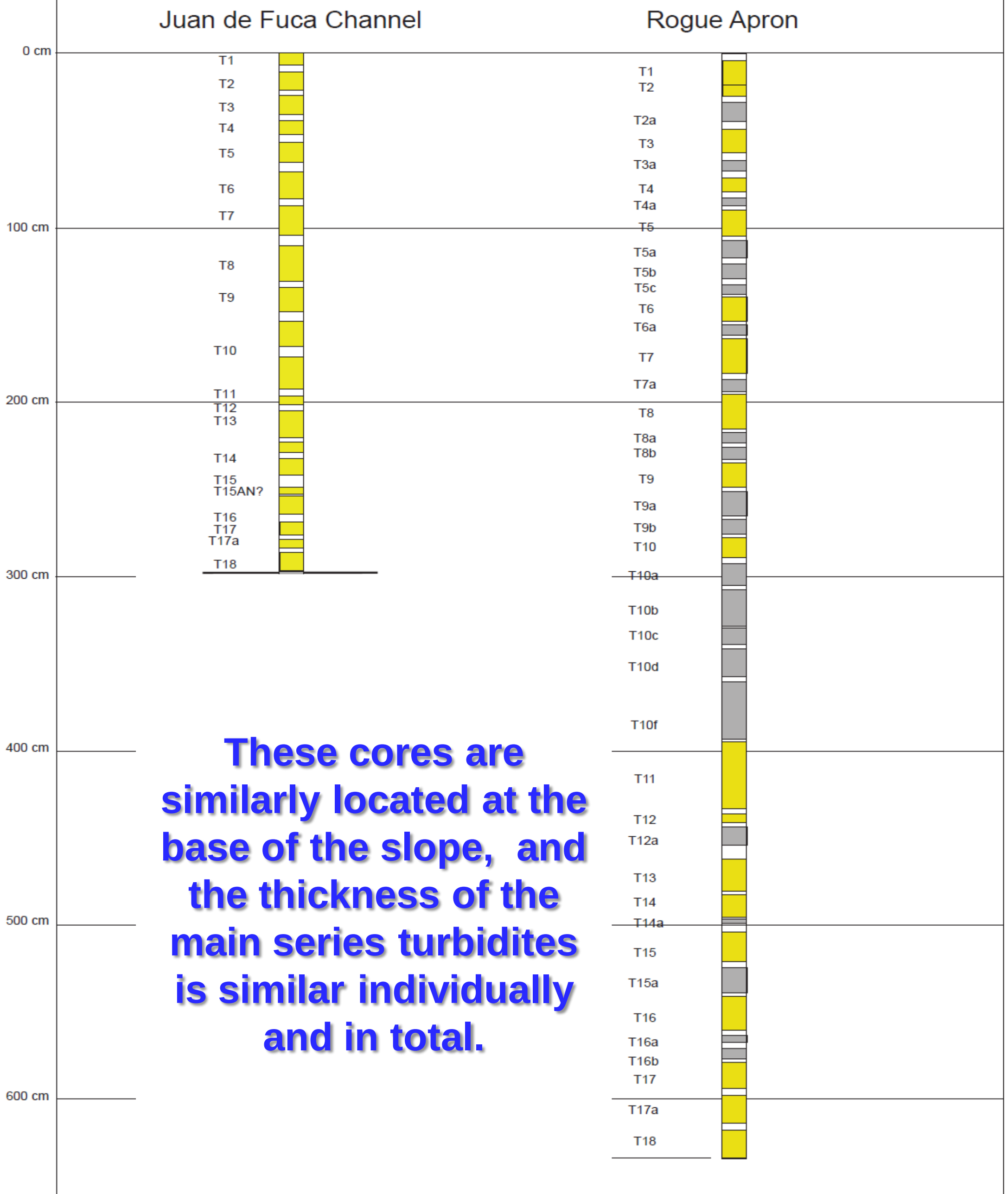
First of all, they are turbidites.
They have sharp bases, fining upward sequences, have limited quantities of broken biogenic material etc. They do not have the characteristics of hyperpycnal flows, that is waxing then waning grain size profiles.



Many of the thin u
from upper slope a
microfossils and h
are most consiste



Why is the JDF Holocene section only half the thickness of that at Rogue?



These cores are similarly located at the base of the slope, and the thickness of the main series turbidites is similar individually and in total.

Schematic comparison of stratigraphic sequences at Juan de Fuca Channel and Rogue Apron at true scale.

What is the difference?

Below the JDF core diagram, we add four units that represent the difference between the two sites.

1) The total thickness of mud turbidites from Rogue Apron;

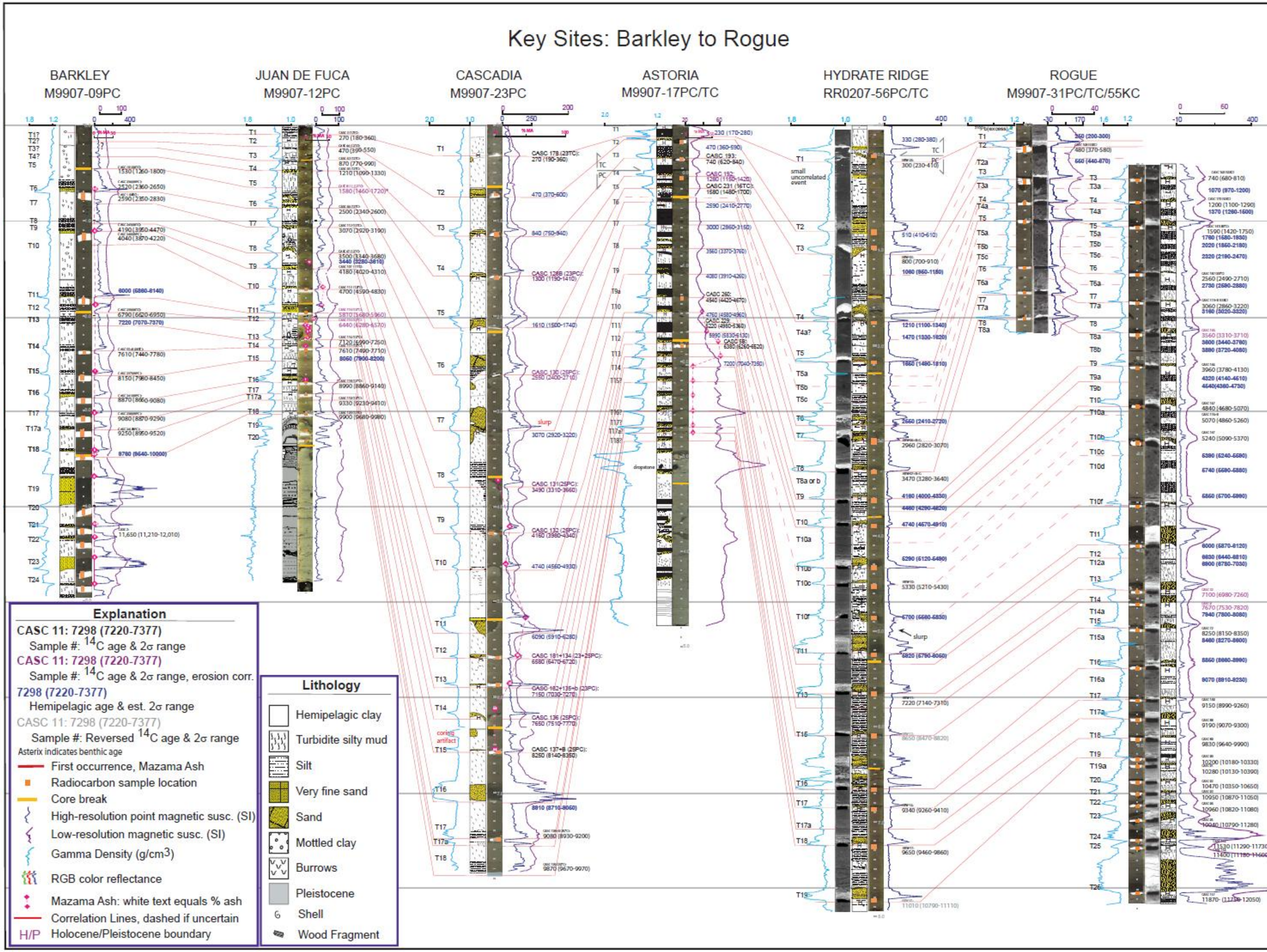
2) The increased overall thickness of Rogue turbidites, 15% greater than JDF, is added to both mud and sand turbidites; and

3) The 150% difference in hemipelagic sedimentation rate (Goldfinger et al., 2012);

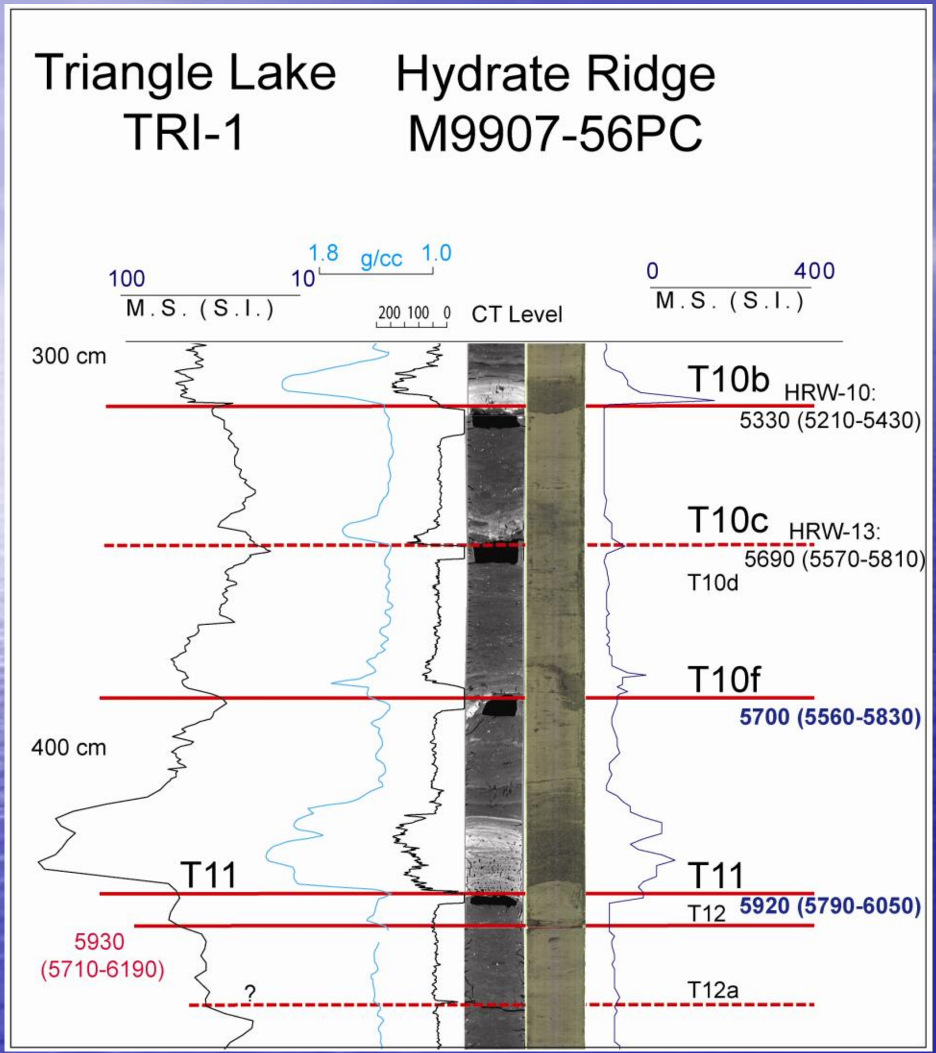
4) The difference in basal erosion at the turbidite bases, compiled from Goldfinger et al (2012).

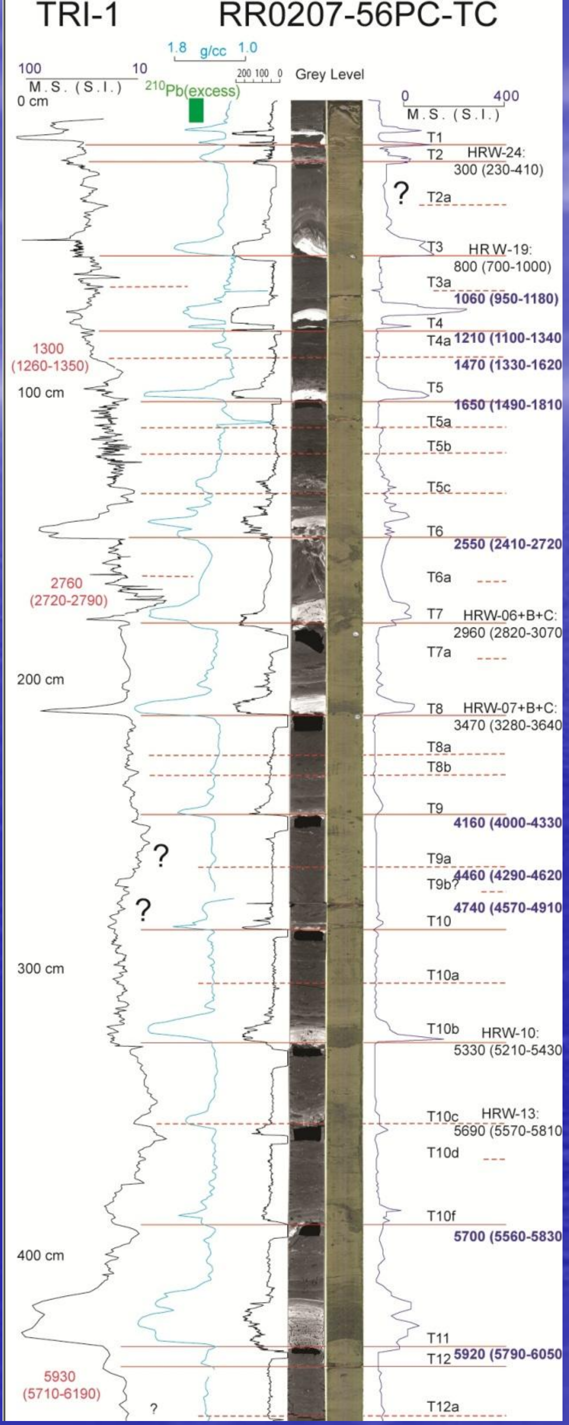
The net difference in Holocene section thickness is ~ 20 cm or 3.1%.

The difference is mostly attributable to the presence of 23 southern Cascadia turbidites present at Rogue Apron.

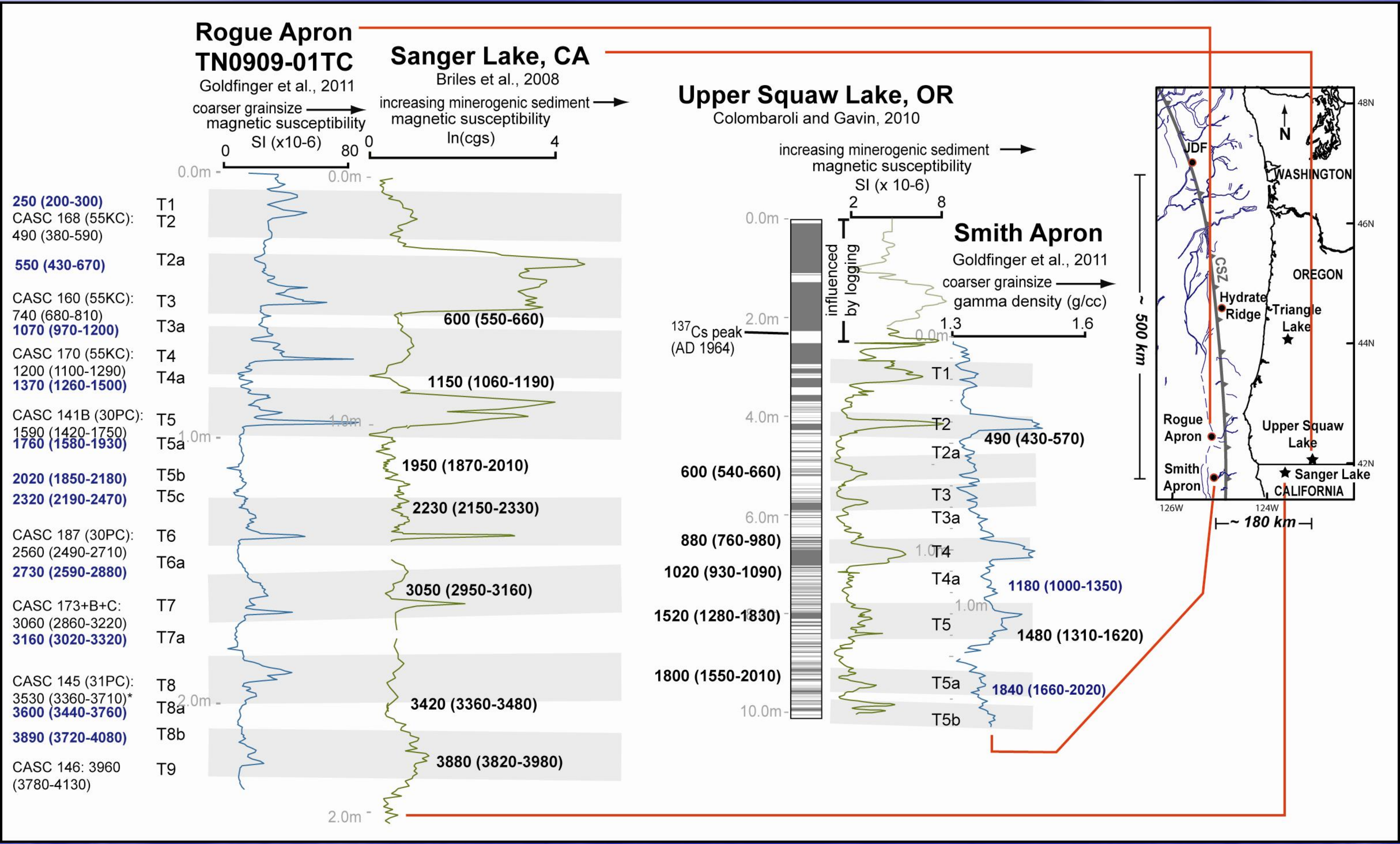

Key Sites: Barkley to Rogue
BARKLEY
M9907-09PC
JUAN DE FUCA
M9907-12PC
CASCADIA
M9907-23PC
ASTORIA
M9907-17PC/TC
HYDRATE RIDGE
RR0207-56PC/TC
ROGUE
M9907-31PC/TC/55KC
0 cm
100 cm
200 cm
300 cm
400 cm
500 cm
600 cm
700 cm
800 cm
Explanation
CASC 11: 7298 (7220-7377)
Sample #: 14C age & 2σ range
CASC 11: 7298 (7220-7377)
Sample #: 14C age & 2σ range, erosion corr.
7298 (7220-7377)
Hemipelagic age & est. 2σ range
CASC 11: 7298 (7220-7377)
Sample #: Reversed 14C age & 2σ range
Asterix indicates benthic age
First occurrence, Mazama Ash
Radiocarbon sample location
Core break
High-resolution point magnetic susc. (SI)
Low-resolution magnetic susc. (SI)
Gamma Density (g/cm3)
RGB color reflectance
Mazama Ash: white text equals % ash
Correlation Lines, dashed if uncertain
H/P Holocene/Pleistocene boundary
Lithology
Hemipelagic clay
Turbidite silty mud
Silt
Very fine sand
Sand
Mottled clay
Burrows
Pleistocene
Shell
Wood Fragment

Multiple lines of evidence



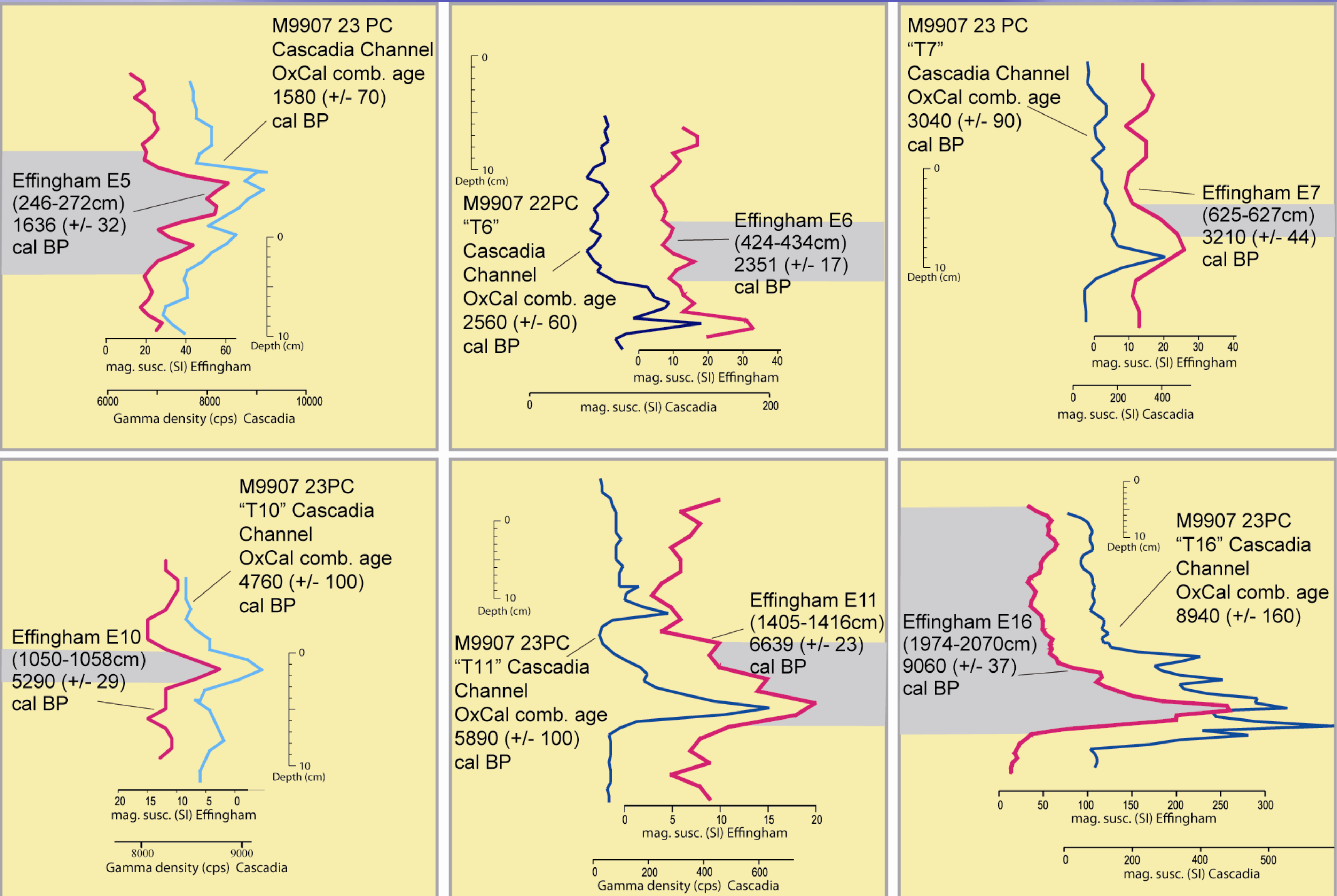


While the land record extends 2-4 ka, the lake record goes back at least to 10,000 years, much like the marine record…



Rogue Apron TN0909-01TC
Goldfinger et al., 2011
coarser grainsize
magnetic susceptibility SI (x10-6)
0
80
Sanger Lake, CA
Briles et al., 2008
increasing minerogenic sediment
magnetic susceptibility ln(cgs)
0
4
0.0m
1.0m
2.0m
250 (200-300)
CASC 168 (55KC): 490 (380-590)
550 (430-670)
CASC 160 (55KC): 740 (680-810)
1070 (970-1200)
CASC 170 (55KC): 1200 (1100-1290)
1370 (1260-1500)
CASC 141B (30PC): 1590 (1420-1750)
1760 (1580-1930)
2020 (1850-2180)
2320 (2190-2470)
CASC 187 (30PC): 2560 (2490-2710)
2730 (2590-2880)
CASC 173+B+C: 3060 (2860-3220)
3160 (3020-3320)
CASC 145 (31PC): 3530 (3360-3710)*
3600 (3440-3760)
3890 (3720-4080)
CASC 146: 3960 (3780-4130)
T1
T2
T2a
T3
T3a
T4
T4a
T5
T5a
T5b
T5c
T6
T6a
T7
T7a
T8
T8a
T8b
T9
600 (550-660)
1150 (1060-1190)
1950 (1870-2010)
2230 (2150-2330)
3050 (2950-3160)
3420 (3360-3480)
3880 (3820-3980)
Upper Squaw Lake, OR
Colombaroli and Gavin, 2010
increasing minerogenic sediment
magnetic susceptibility SI (x 10-6)
2
8
0.0m
2.0m
4.0m
6.0m
10.0m
influenced by logging
137Cs peak (AD 1964)
600 (540-660)
880 (760-980)
1020 (930-1090)
1520 (1280-1830)
1800 (1550-2010)
Smith Apron
Goldfinger et al., 2011
coarser grainsize
gamma density (g/cc)
1.3
1.6
490 (430-570)
1180 (1000-1350)
1480 (1310-1620)
1840 (1660-2020)
~ 500 km
~ 180 km
N
JDF
WASHINGTON
OREGON
CALIFORNIA
CSZ
Hydrate Ridge
Triangle Lake
Rogue Apron
Upper Squaw Lake
Smith Apron
Sanger Lake
48N
46N
44N
42N
126W
124W

Effingham inlet vs. Cascadia Channel



Onshore-Offshore space-time diagram for the most recent ~ 2800 years.

(Filled symbols are marine data, open symbols land data; smaller open symbols are bulk peat ages, given lower weighting here.)

Stratigraphic correlation for offshore data shown in blue dashed lines.

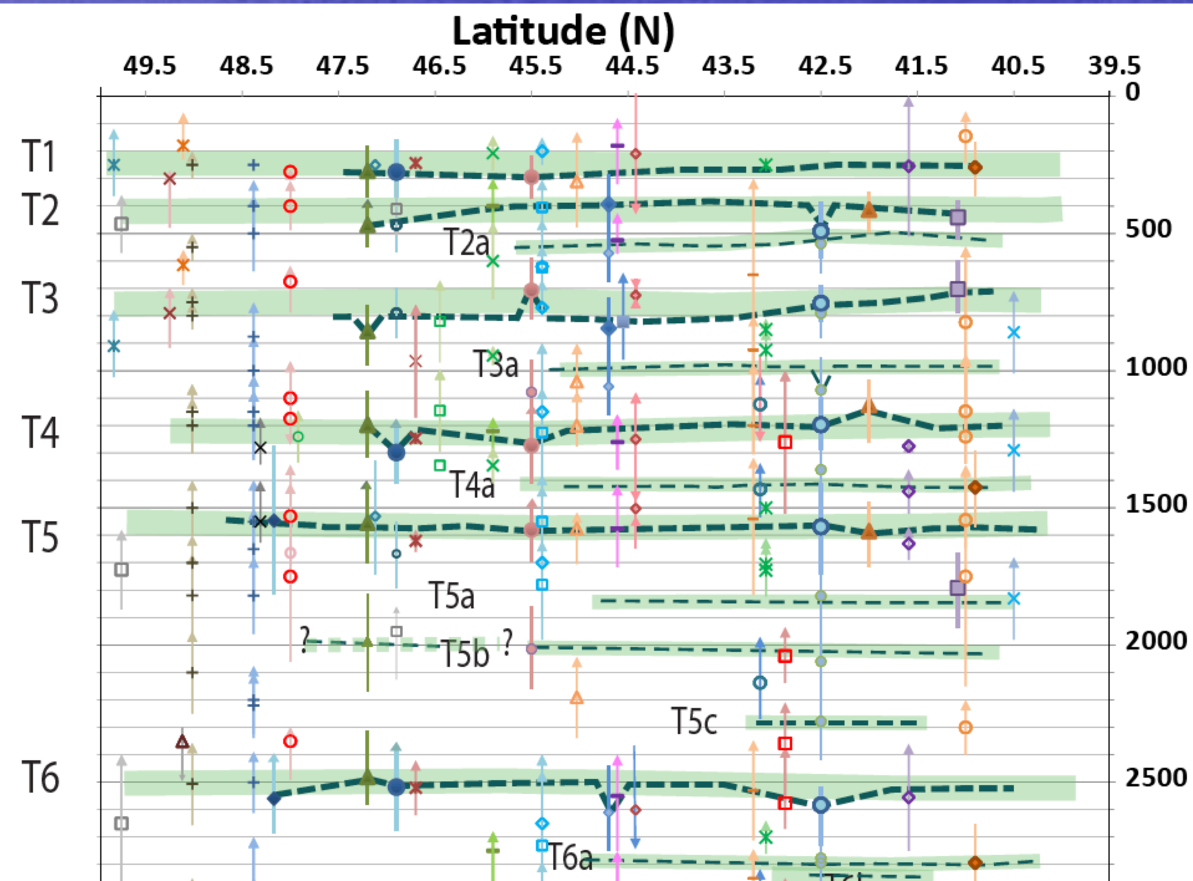
Land Data

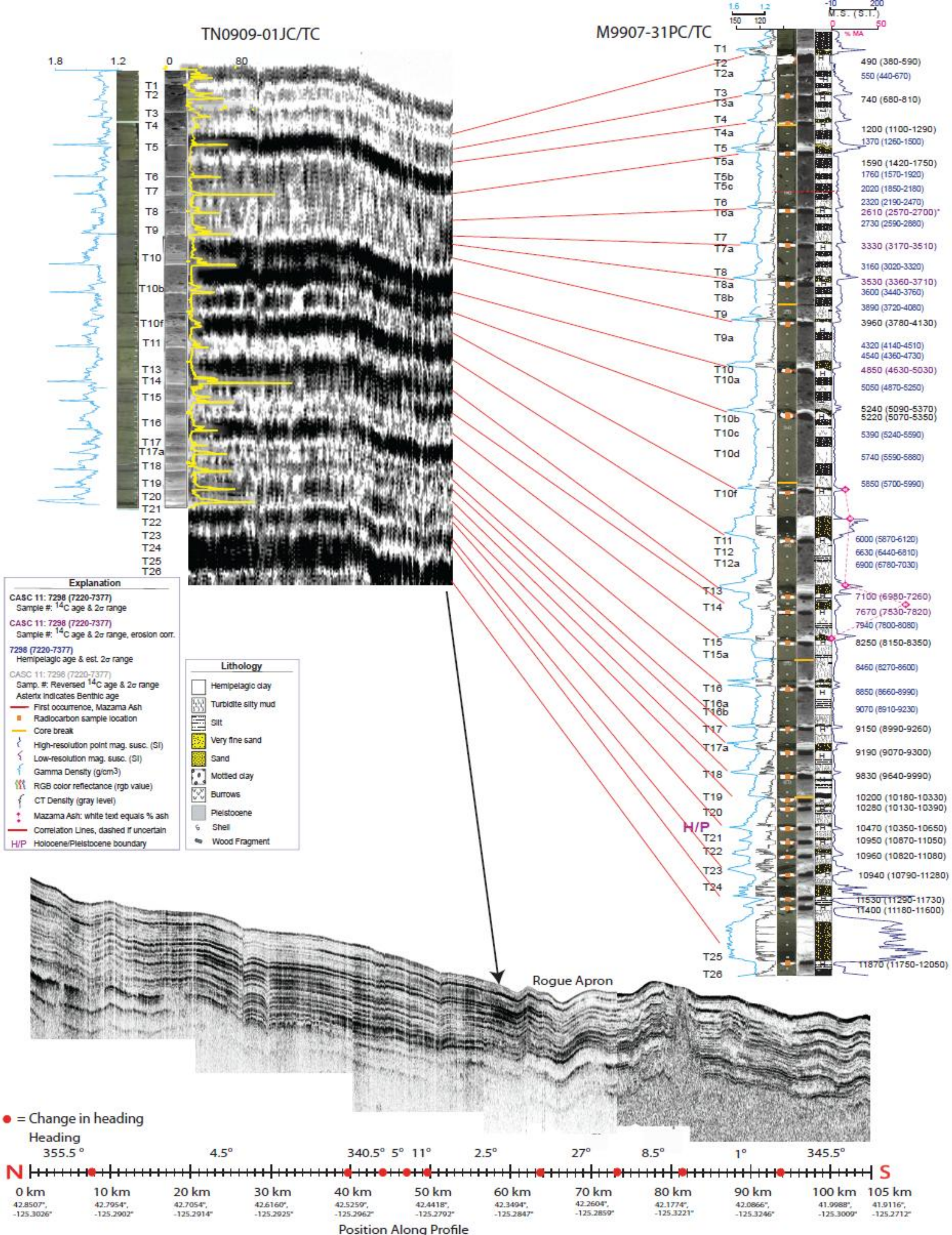
- Deserted Lake[20]
- Port Alberni[11]
- Tofino[7,17,18]
- Effingham[11,45]
- Catala Lake[9]
- Kakawis Lake[25]
- Saanich Inlet[6]
- Saanich Varves[6]
- Discovery Bay[41]
- Swantown[40]
- Cultus Bay[46]
- Copalis River[2]
- Johns River[38]
- Willapa Bay[2,3,47]
- Long Beach WA[37]
- Ecola Creek[14,34]
- Ecola 2007[44]
- Netarts Shennan[39,24]
- Netarts Marsh[12,13]
- Salmon River[29]
- Yaquina Bay[14]
- Alsea Bay[14,31]
- Coquille River[43]
- Coos Bay2[30,27,28]
- Bradley Lake[23]
- Sixes River[43]
- Humboldt Bay[33]
- Eel River[33]
- Lagoon Creek[15,16]

Marine Data

- Barclay Canyon
- Barkley Canyon H
- Juan de Fuca
- Juan de Fuca H
- Cascadia Channel
- Cascadia Channel H
- Cascadia 1996[48]
- Astoria Channel
- Astoria Channel H
- Astoria 1996[48]
- Hydrate Ridge
- Hydrate Ridge H
- Rogue Apron
- Rogue Apron H
- Smith Apron
- Klamath Canyon
- Trinidad Plunge Pool
- Eel Channel

Land Data





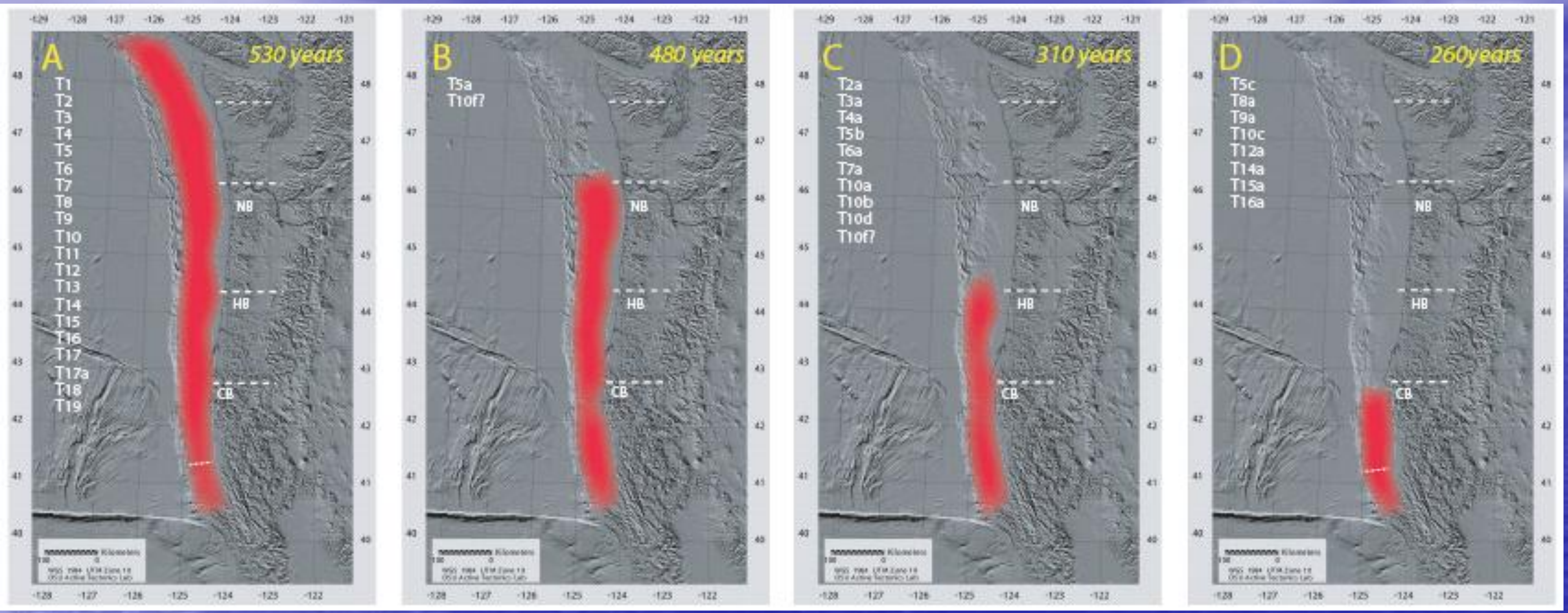
Multiple lines of evidence, continued…

2-6 kHz chirp reflection profiles image the Holocene section with vertical resolution of ~ 18 cm.

Direct correlation with cores is straightforward with depth conversion, allowing along strike correlation of the larger sandy turbidites for 100's of km along strike.

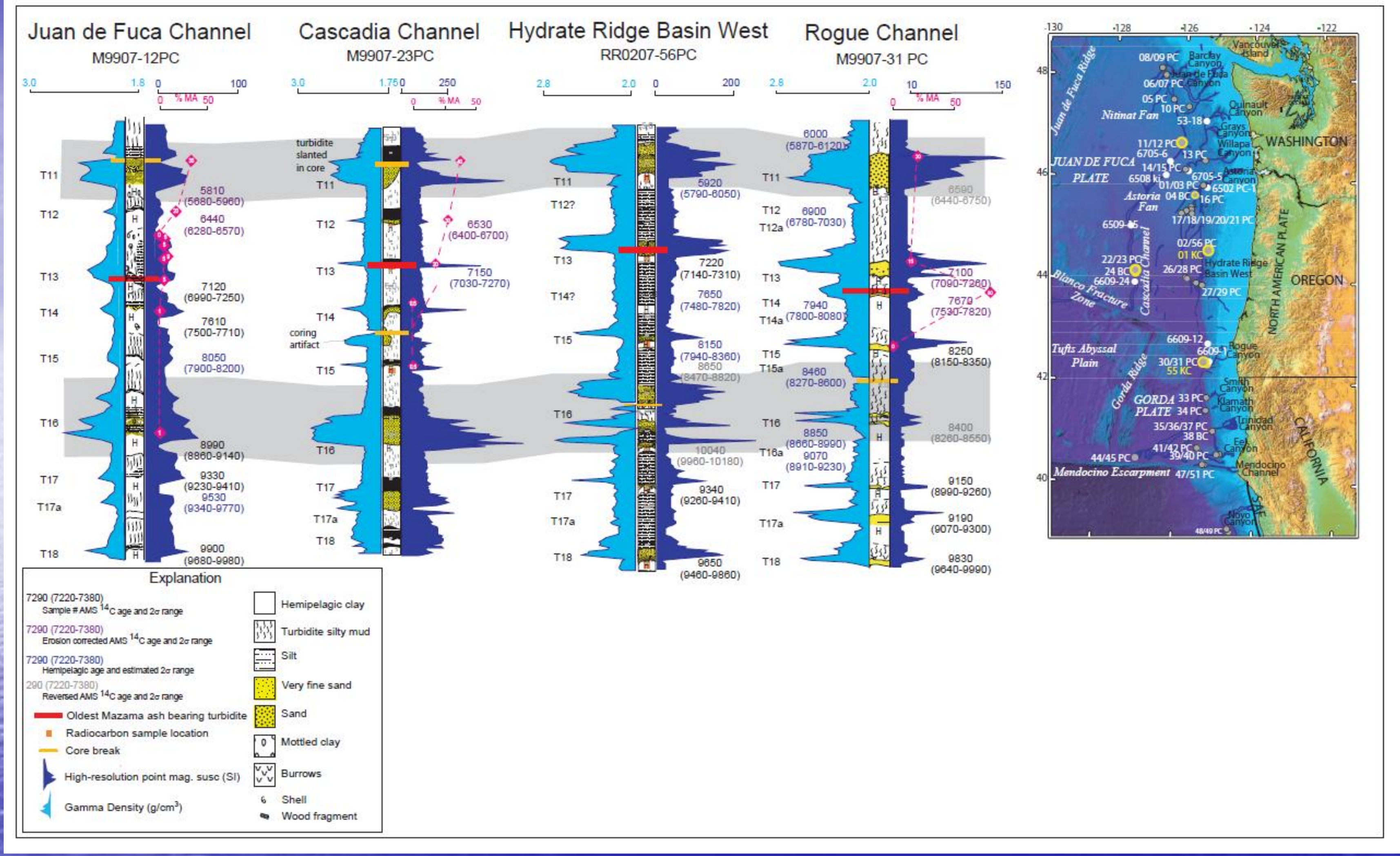
This example, centered on Rogue apron, shows 108 km of margin parallel profile, 5 km seaward of the deformation front.

Now the fun begins…..



Rupture lengths from paleoseismic data, past 10,000 years. Segment boundaries are roughly compatible with ETS segment boundaries proposed by Brudzinski et al., 2007, though both sets of boundaries are quite crude.

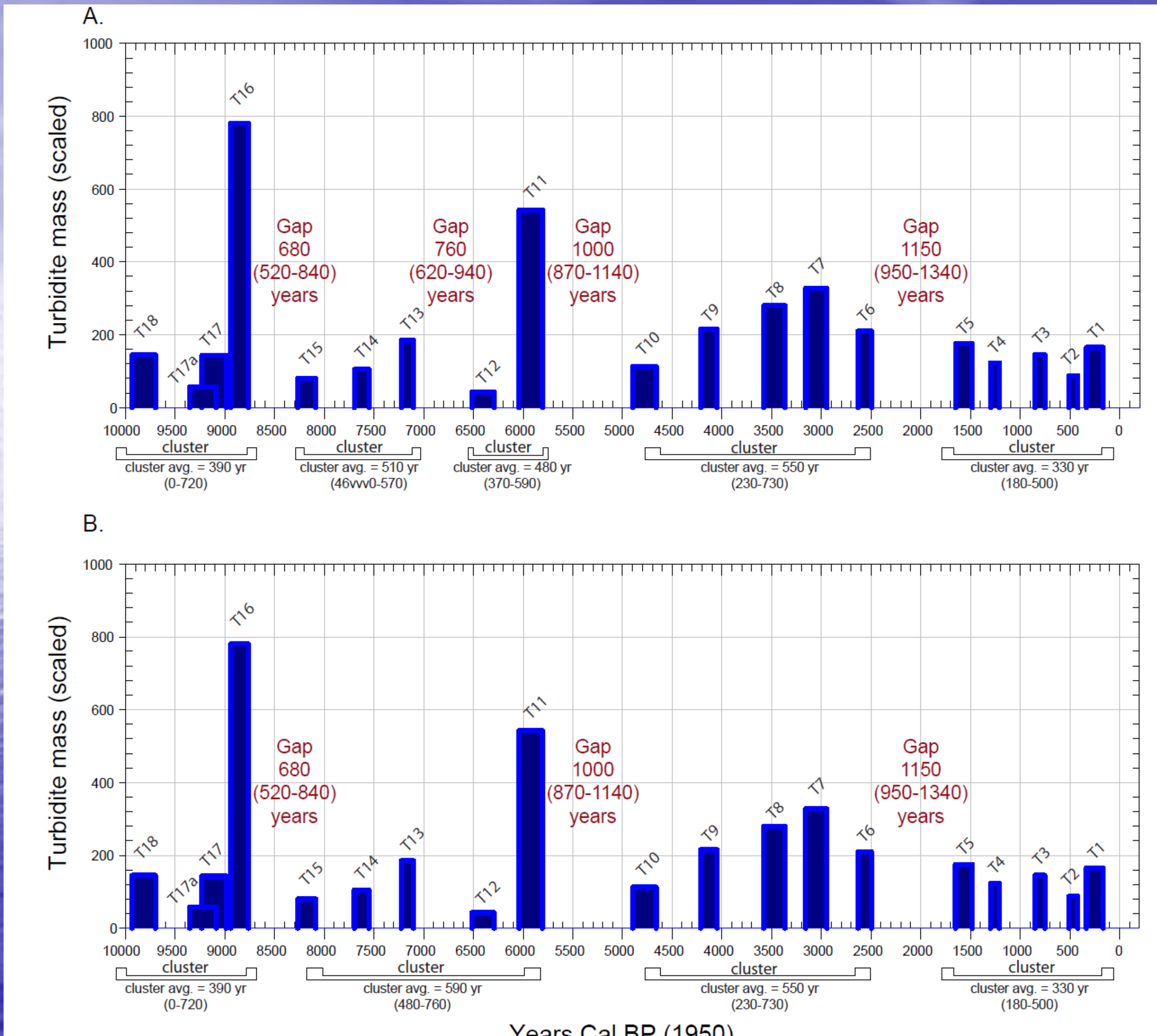
While recurrence interval is ~ 500 years in northern Cascadia, it is only 220-220 years in the south. (220 years in the past ~ 3000 years). The NSAF recurrence during this time is similar, ~200 years.



Outsized Events?

The well known AD 1700 earthquake is thought to be Mw=9.0, yet it is only "average" in the turbidite record. There are a number of others like it in the 43 event record over 10,000 years. The largest events are T11 and T16, which is about three times the mass of the ~ M9.0 1700 turbidite.

Similar to Tohoku?



What about clustering?

There seems to be a poorly developed clustering, suggested here.

It certainly makes a difference whether the next expected event is part of a cluster or not, if clusters exist, and if the next event reflects a repeat of recent behavior. Clustering seems better developed in the latter half of the Holocene. If a repeat were to occur, a gap may be next.

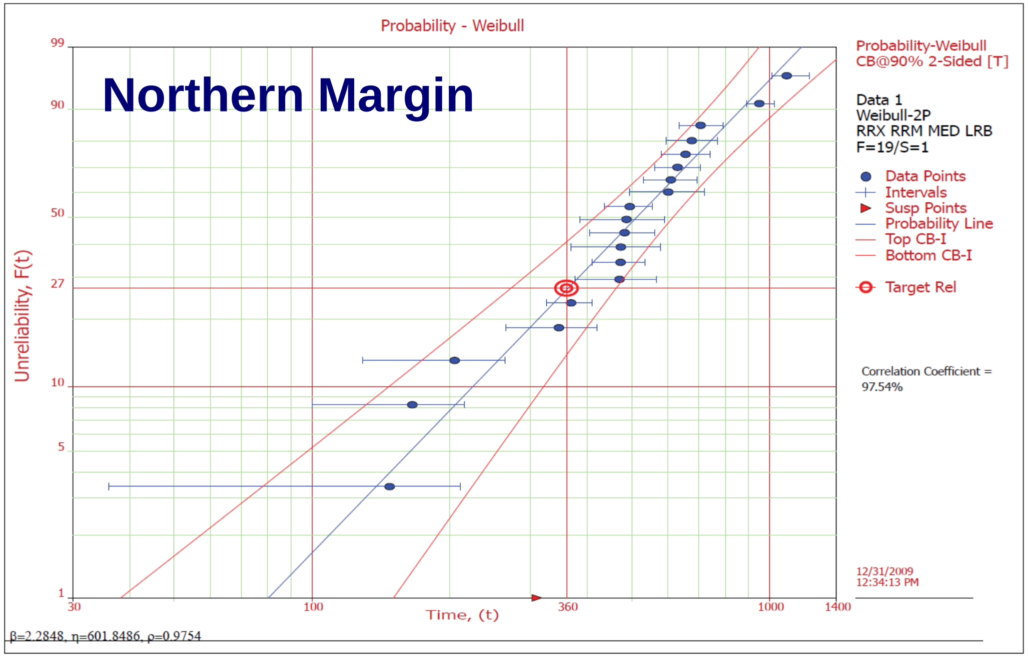
They exist, but

1) do they mean anything, and
2) what can be done about them probabilistically?

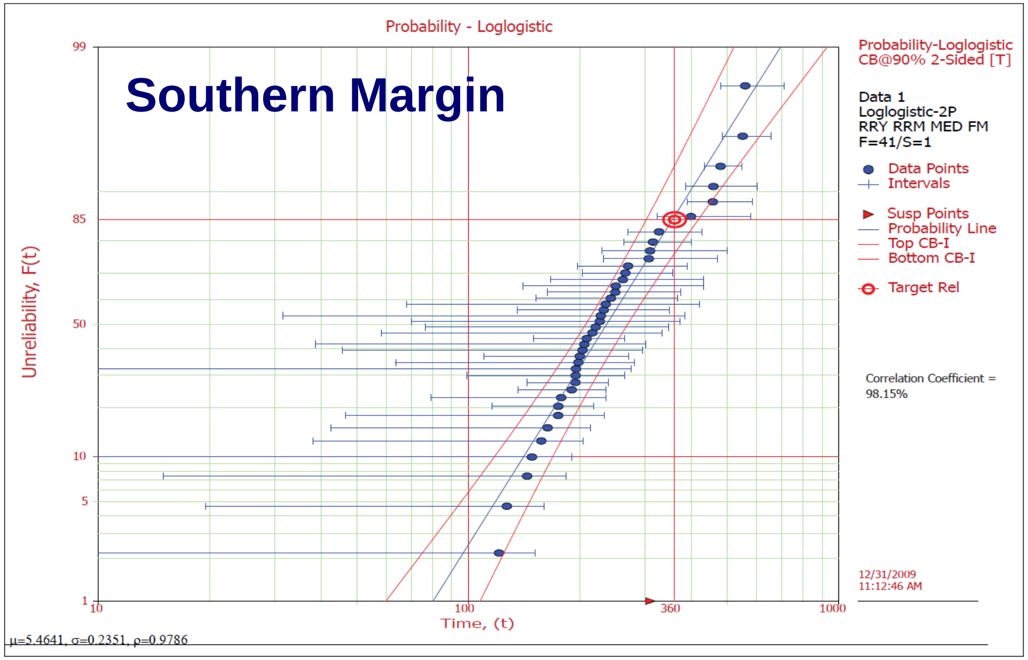
For the northern margin, probabilities are relatively low, many intervals longer than 360 years are in the paleoseismic record. The failure analysis suggests at 360 years, 25% of repeat times will have been exceeded. Conditional probability in 50 years is 12% (7-15%).

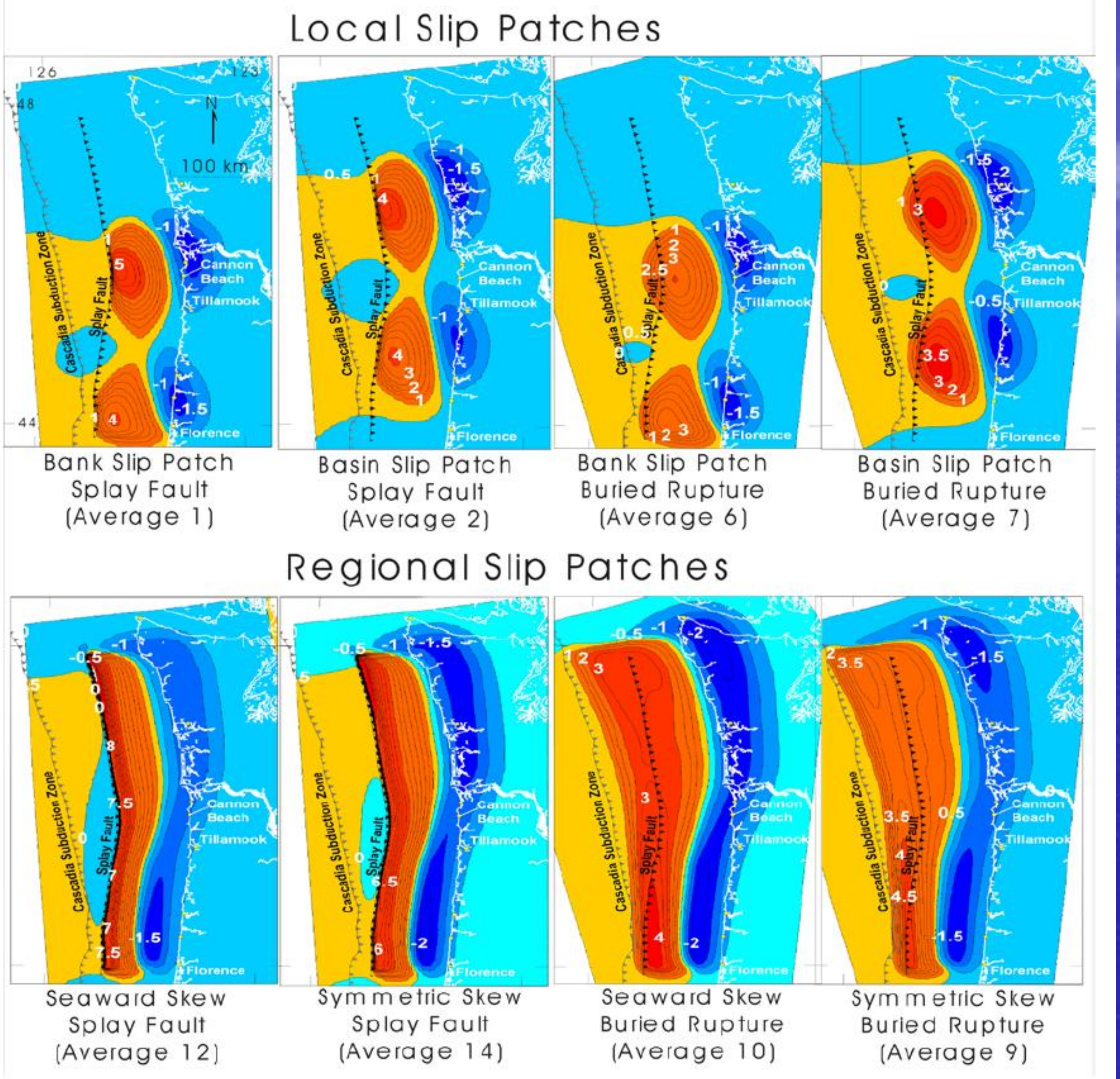
For the southern margin, 70-93% of repeat times will have been exceeded. Conditional probability in 50 years is 37% (32-42%).

A



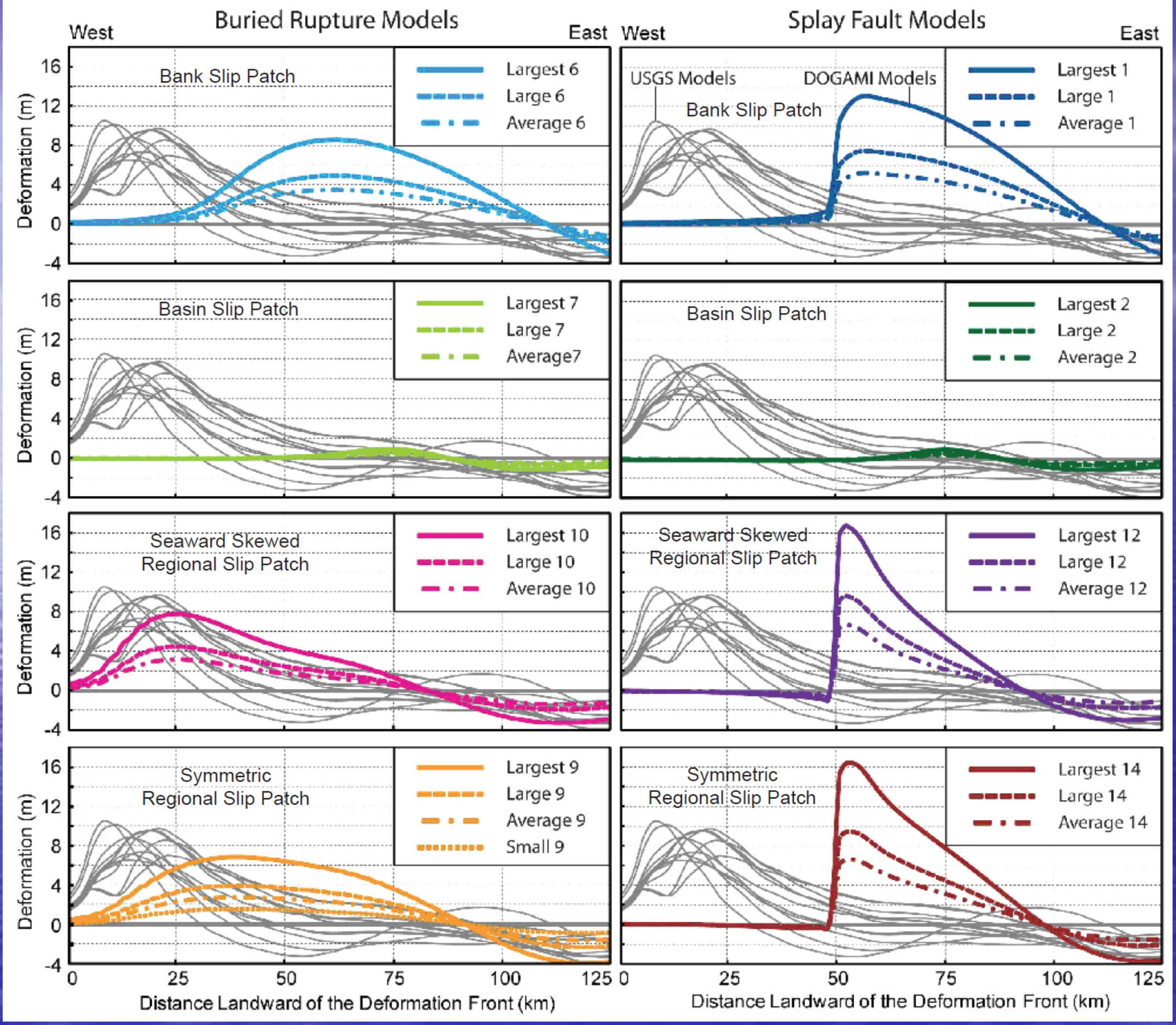
B





Probabilistic tsunami assessment, State of Oregon for Cannon Beach

Analysis uses paleoseismic sources, relative sizes and frequencies, along with attempts to match onshore paleo-inundations and observed subsidence.


Buried Rupture Models
Splay Fault Models
West
East
Bank Slip Patch
Largest 6
Large 6
Average 6
USGS Models
DOGAMI Models
Largest 1
Large 1
Average 1
Basin Slip Patch
Largest 7
Large 7
Average7
Largest 2
Large 2
Average 2
Seaward Skewed
Regional Slip Patch
Largest 10
Large 10
Average 10
Largest 12
Large 12
Average 12
Symmetric
Regional Slip Patch
Largest 9
Large 9
Average 9
Small 9
Largest 14
Large 14
Average 14
Deformation (m)
Distance Landward of the Deformation Front (km)
Distance Landward of the Defomation Front (km)

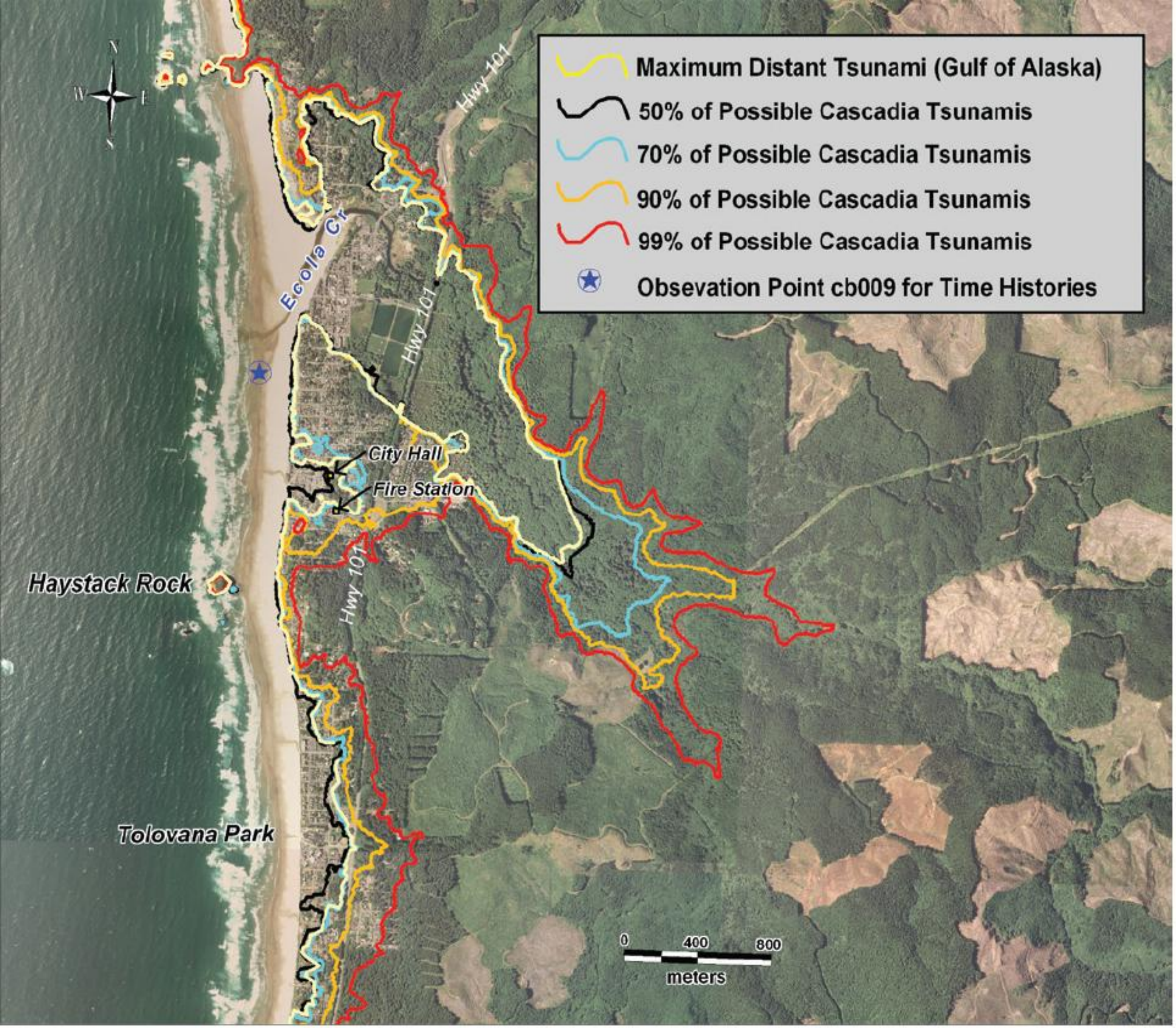


Figure 50. Key scenario inundation scenarios at Cannon Beach, Oregon. All inundation lines are individual tsunami scenarios that most closely match the listed confidence lines (see Figure 47). Mapped scenarios: ~50 percent = Average 9; 70 percent = Average 14; 90 percent = Large 14; ~99 percent = Largest 14.

Probabilistic tsunami assessment, State of Oregon for Cannon Beach

Analysis uses paleoseismic sources, relative sizes and frequencies, along with attempts to match onshore paleo-inundations and observed subsidence.

Thanks for your attention!

Quantifying Geologic Inference

As with most geological interpretations, we informally use the Judge Wapner method, considering "the preponderance of the evidence". There is rarely a single criteria that is the "smoking gun" in geology.

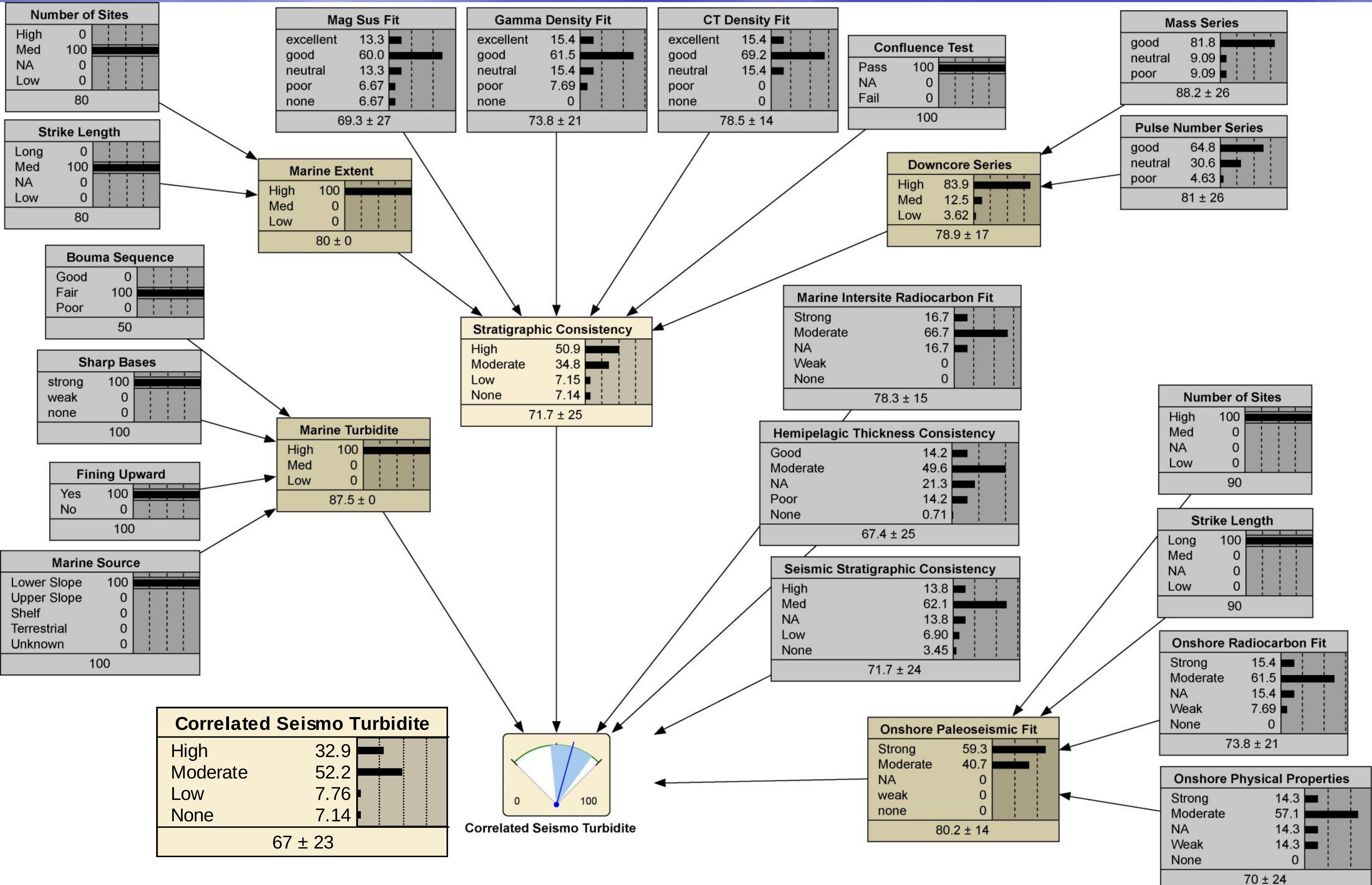
But there is a way to quantify data and estimate the probability of a given hypothesis using Bayes theorem.

Bayes theorem considers the probability of a hypothesis, given the data. This can be done with or without prior information.

This is the opposite of so called "frequentist" (standard statistics) methods which do not consider multiple hypotheses, or probabilities.

The observables we have to evaluate are:

- Sedimentological character, such as Bouma sequences, fining upward sequences, sharp bases etc.
- Evidence of downslope transport from shallow water
- Geophysical parameter correlation, such as gamma and CT density, magnetic Susceptibility, resistivity, p-wave velocity and others.
- The distance and number of sites that meet threshold criteria for correlation.
- Relative dating tests such as the confluence test
- Downcore parameter series such as mass, number of fining upward units.
- Radiocarbon, Cs137, Pb210 and other dating parameter fits.
- Temporal correlation based on hemipelagic thickness
- Seismic stratigraphic correlation
- Onshore temporal fit
- Onshore stratigraphic correlation
- Onshore strike extent



Bayesian Probabilities of earthquake origin under uncertainty

Preliminary results: probability of correlation given the input data, T1-18 for (JDF, Cascadia, HR, Rogue) and high precision land sites.

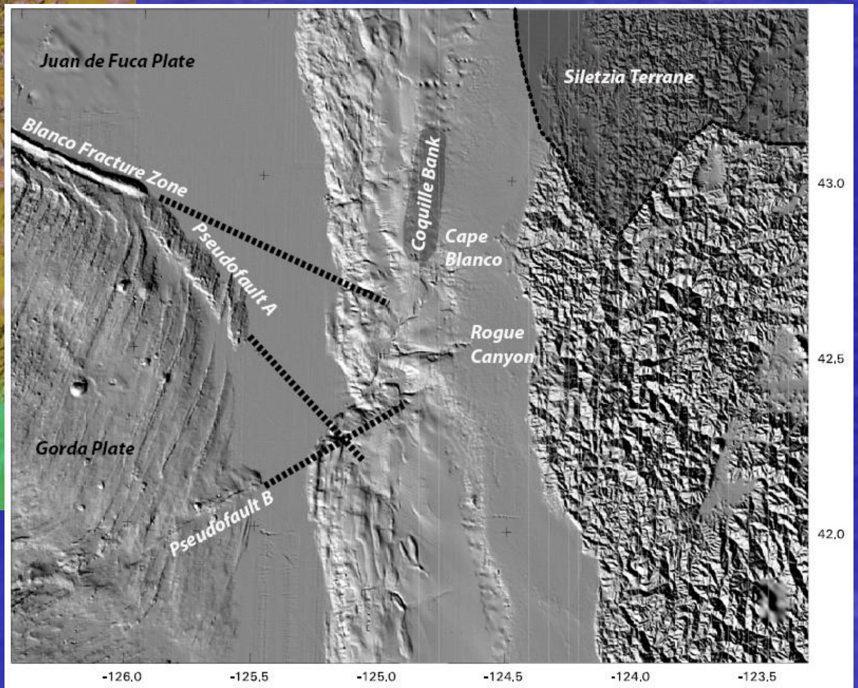
Idnum	freq	finding Correl	probabilities of Correl	P(case)
1	1	*	(0.94 0.06)	4.17444e-008
2	1	*	(0.77 0.23)	4.17444e-008
3	1	*	(0.82 0.18)	4.30094e-008
4	1	*	(0.88 0.12)	4.17444e-008
5	1	*	(0.71 0.29)	4.43127e-008
6	1	*	(0.93 0.07)	4.17444e-008
7	1	*	(0.87 0.13)	4.30094e-008
8	1	*	(0.73 0.27)	4.30094e-008
9	1	*	(0.83 0.17)	4.17444e-008
10	1	*	(0.63 0.37)	4.30094e-008
11	1	*	(0.85 0.15)	4.17444e-008
12	1	*	(0.74 0.26)	4.17444e-008
13	1	*	(0.89 0.11)	4.17444e-008
14	1	*	(0.82 0.18)	4.30094e-008
15	1	*	(0.77 0.23)	4.30094e-008
16	1	*	(0.85 0.15)	4.17444e-008
17	1	*	(0.83 0.17)	4.17444e-008
17a	1	*	(0.81 0.19)	4.30094e-008
18	1	*	(0.79 0.21)	4.17444e-008

Average probability long ruptures= 81%, southern ruptures 64%

Why segments in the south but not the north?

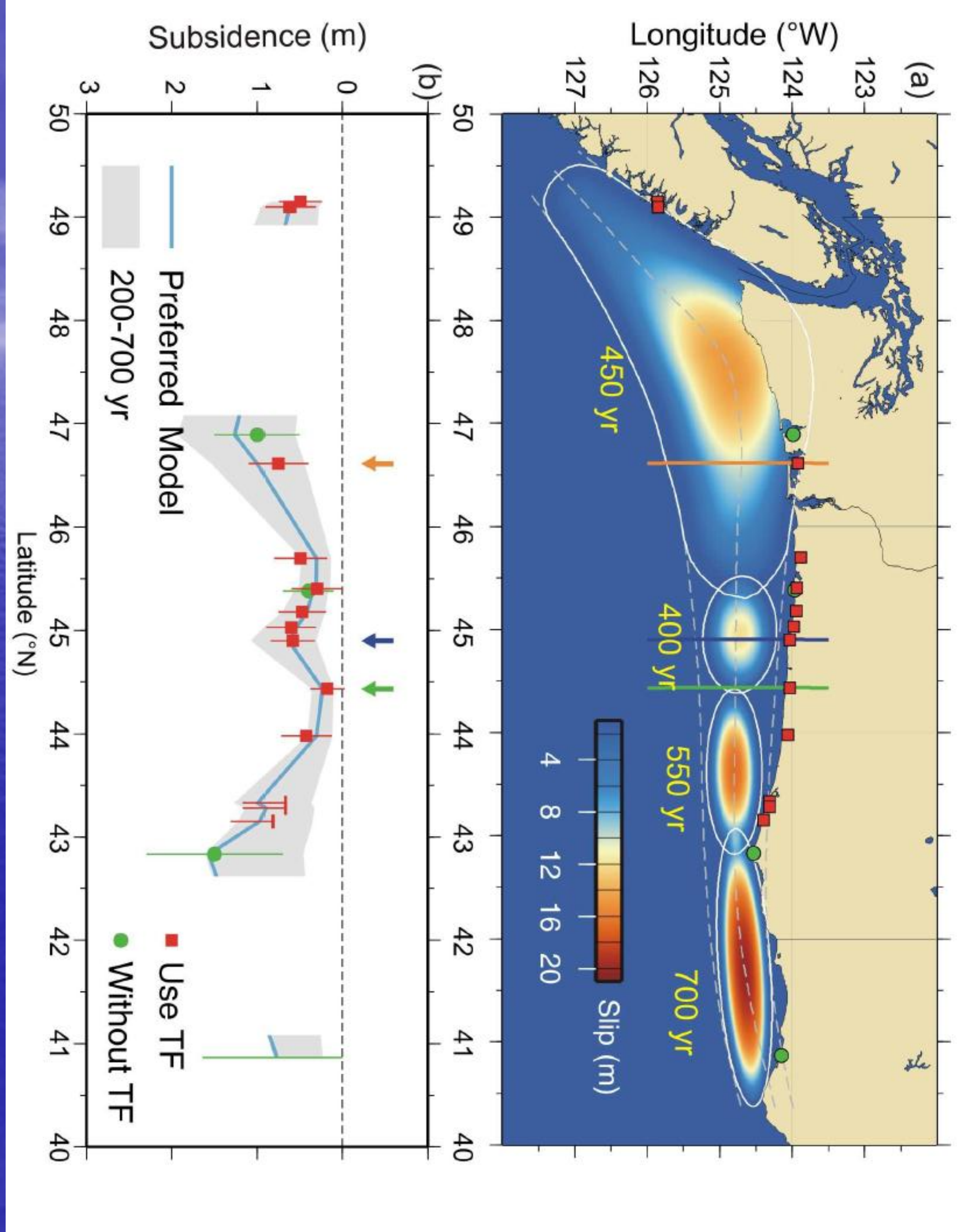
Earthquake frequency and segment size may be linked to sediment supply, which decreases southward, exposing plate roughness and perhaps forearc structure that may be obscured by great sediment thickness in the north-central margin.

The Blanco Fracture Zone two rift propagators, and perhaps the keel of the Klamath Terrane/Siletzia boundary may serve as segment bounding structures.



Evidence of a low slip, low coupling segment boundary in central Oregon is abundant from geodesy and structural geology, and this proposed slip model of the 1700 earthquake. Reasons for this boundary?????

Courtesy of Pei-Ling Wang

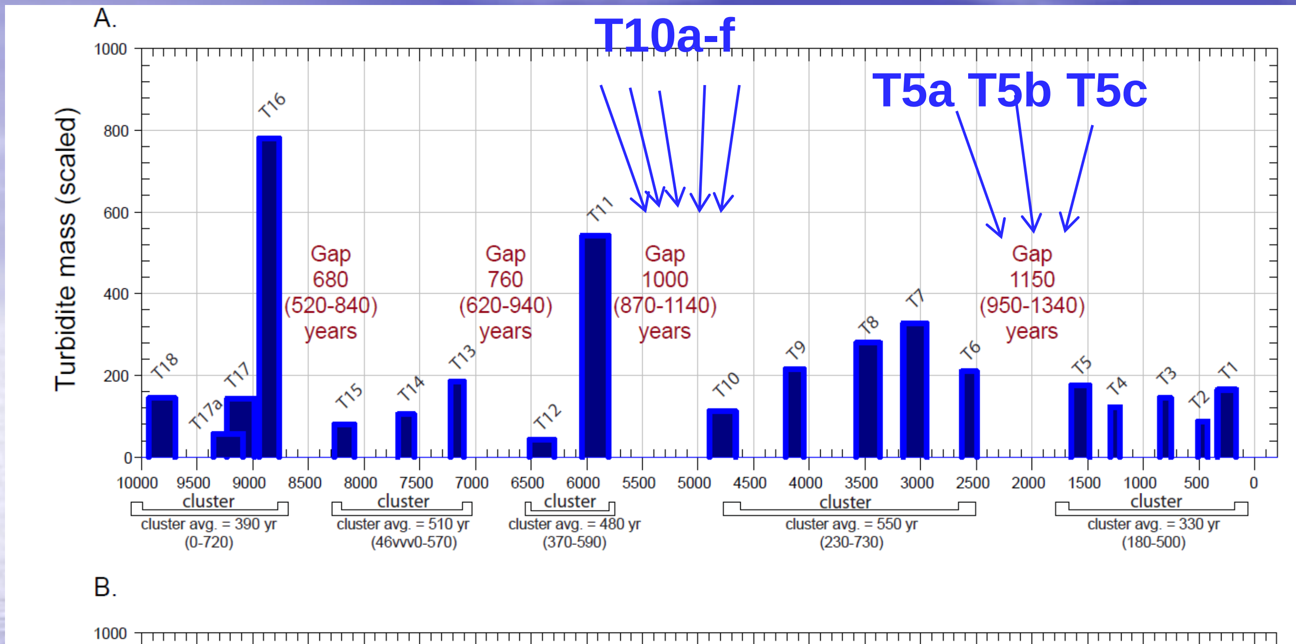


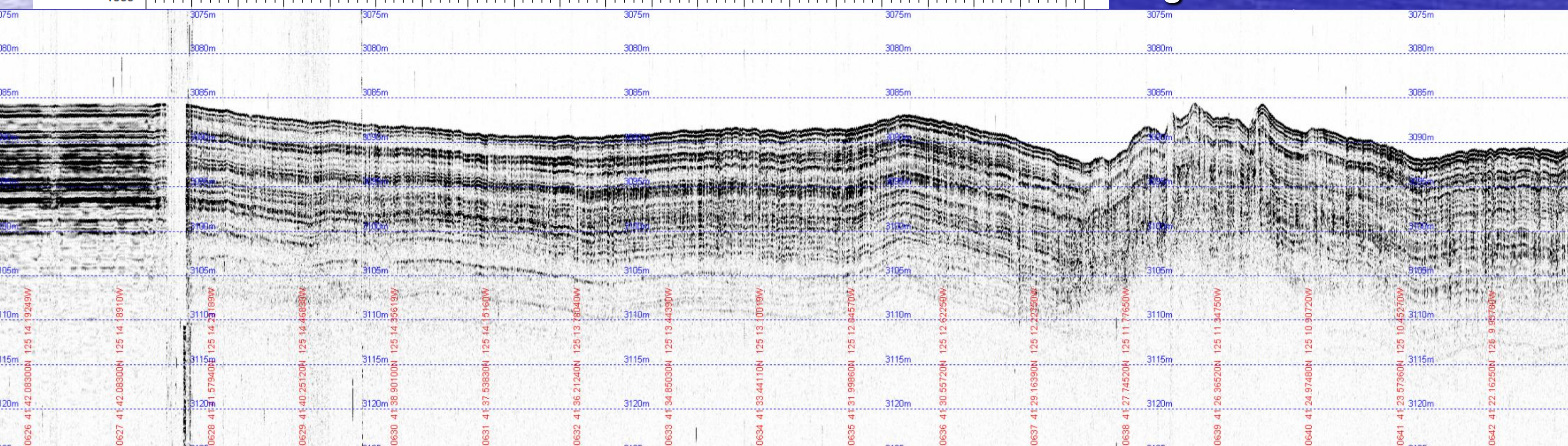
Modeling Rupture in the 1700 Great Cascadia Earthquake Based on High Quality Paleoseismic Observations
Pei-Ling Wang1,2, Kelin Wang2, Andrea D. Hawkes3, Benjamin P. Horton4, Simon E. Engelhart4, Alan R Nelson5, Robert Witter6, Yuki Sawai7 AGU Fall meeting 2011.

Along the southern margin, clusters do not exist in a temporal sense.

But, the larger events are clustered as in the north, with smaller events interspersed in the long gaps, so if one discounts the smaller events, then there remain “moment clusters”

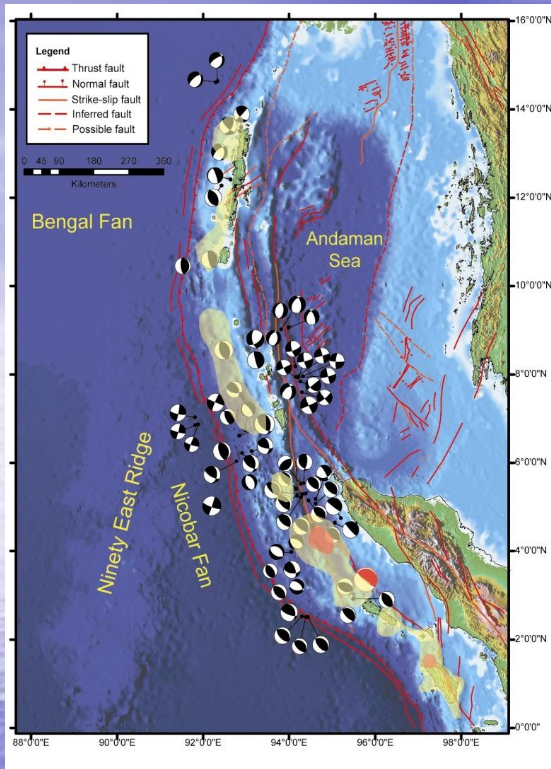
Arguments about whether





Earthquake clusters you can see!

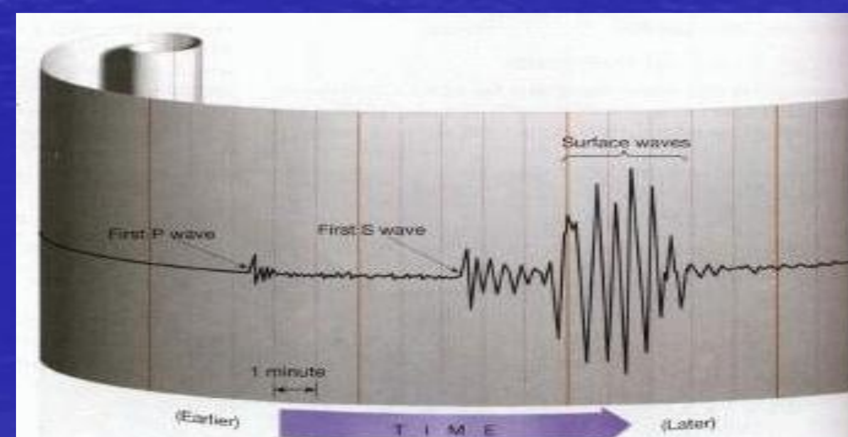
But wait…Why do they correlate?

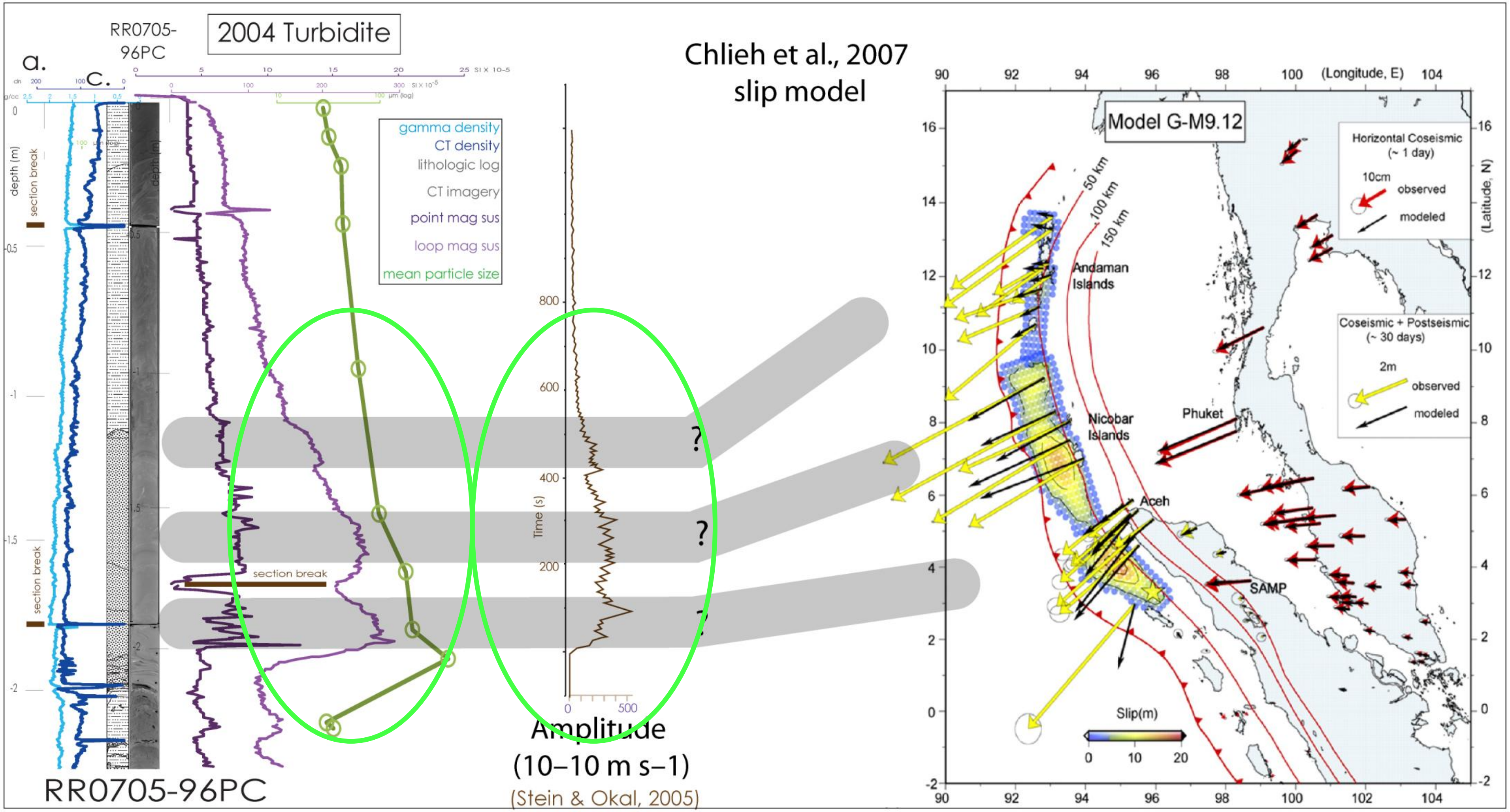


These channels have little in common above the confluences, so it doesn't seem reasonable to call upon geologic similarities to account for the correlation.

The only thing these signatures have in common is the earthquake. We suspect that the signatures represent unique energy signatures of the source mechanism, a "paleoseismogram"

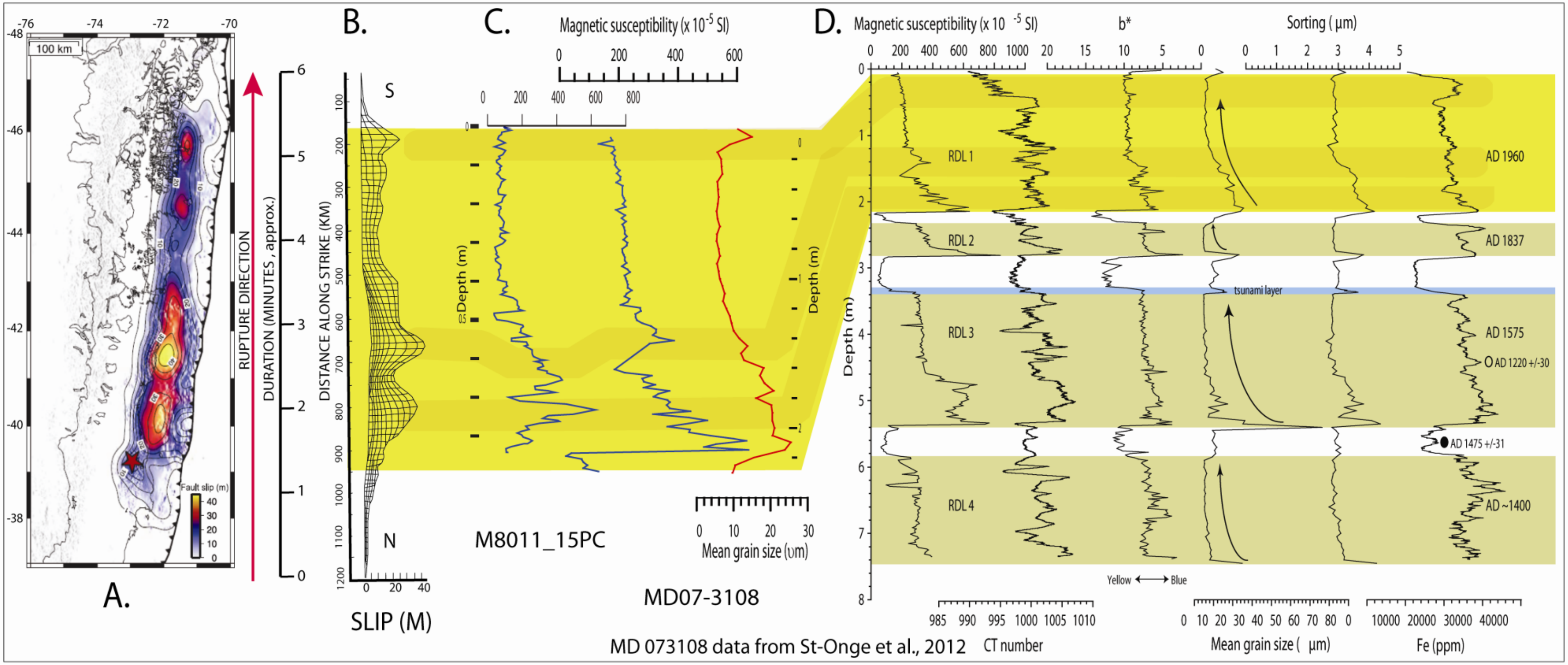
This hypothesis predicts that a long multi-segment rupture like Sumatra, should produce a multipulse turbidite…. We think that this signal can overprint all the confounding factors like hydrodynamics, complex and retrogressive failures, and topography in the case of very large earthquakes. We also predict it will fail for smaller earthquakes





The 2004 event in 96 PC/TC is well represented in 96PC as a 1.5-2m three pulse sandy event at the seafloor. Pb210 and Cs 137 confirm a very young age.

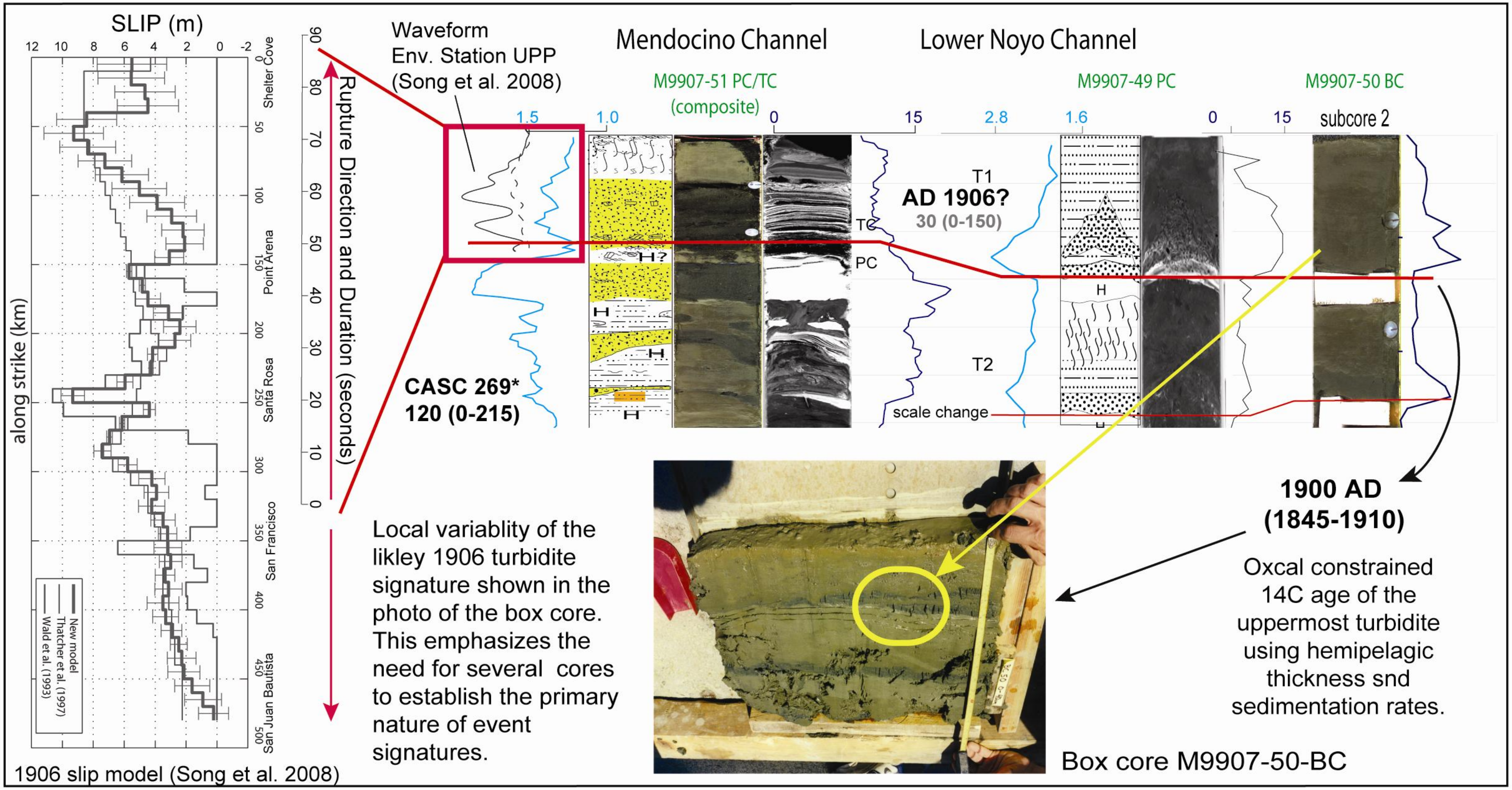
The three-pulse base is compared here to the time history of moment release (brown curve).



It gets better…

The 1960 Chile turbidite appears in numerous cores in the trench and in fjords as a two pulse sandy event at the seafloor. Pb210 and Cs 137 confirm the 1960 age.

The two-pulse base is compared here to the time history of moment release from Moreno et al (2009) and Barrientos and Ward (1990).

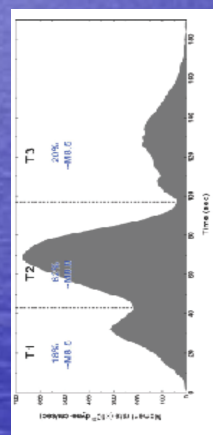


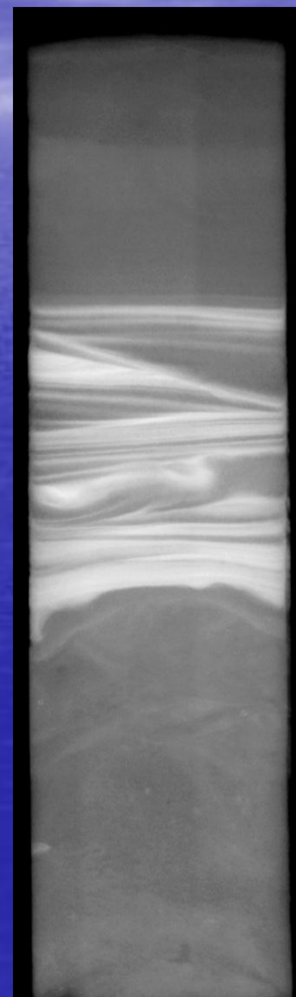
And better…

The 1906 San Francisco turbidite appears in numerous cores offshore as a two pulse sandy event at the seafloor. 14C and sed. rates confirm the 1906 age. The two-pulse base is compared here to the time history of moment release from Song et al (2008) and the UPP waveform envelope.

KT-11-17 ST.6

Moment rate plot from Lee et al, 2011

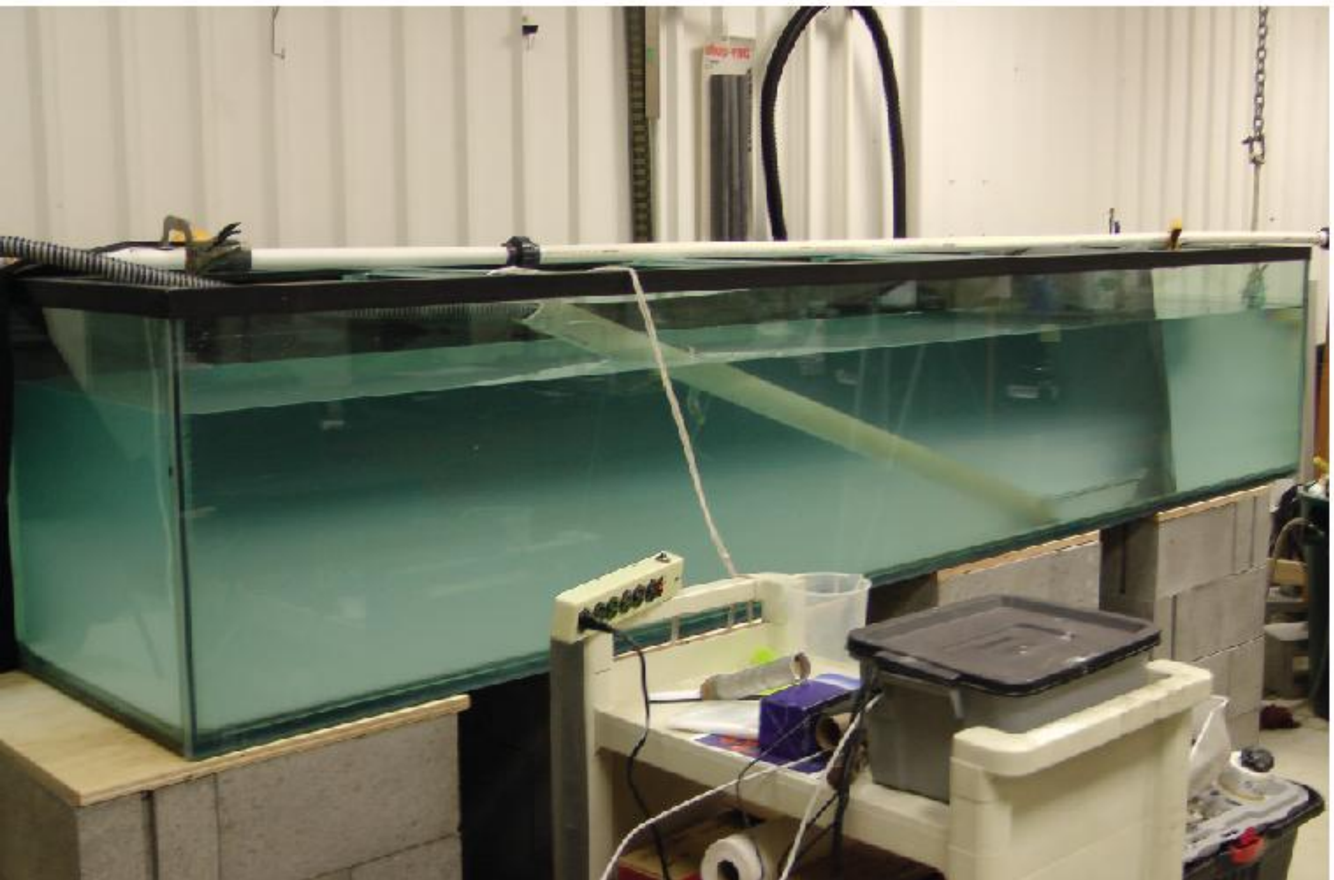




Tohoku 2011 turbidite

More cores in better locations (less proximal) are needed to evaluate the Tohoku moment rate vs. Turbidite structure.

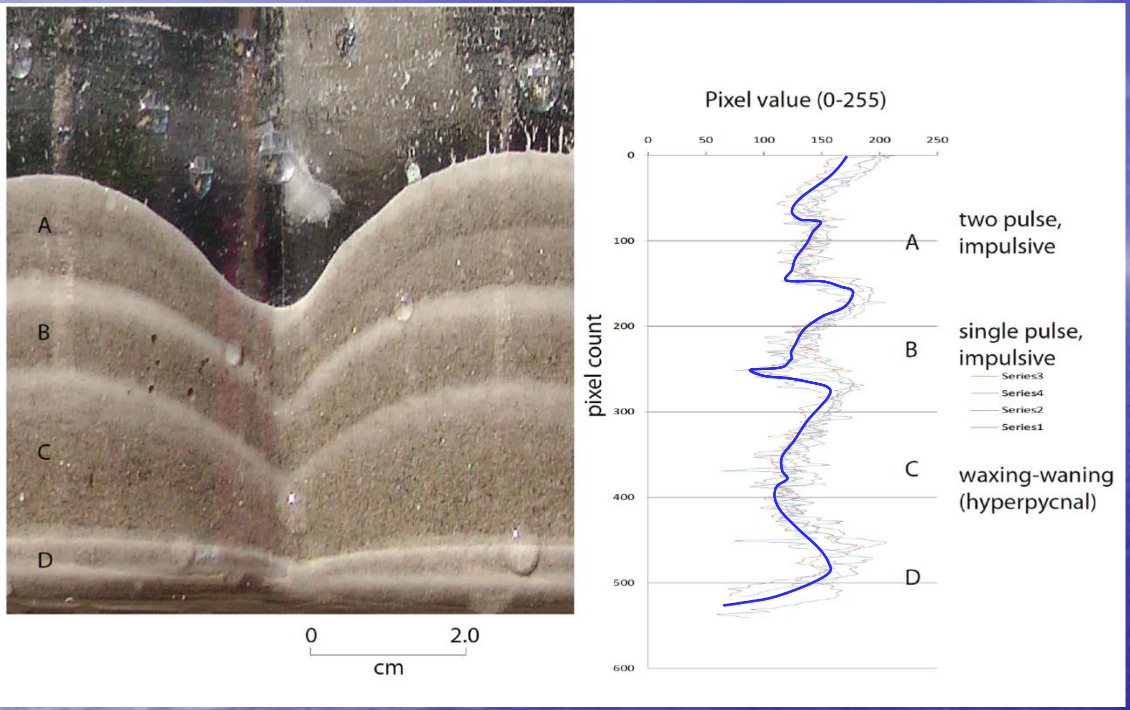
Courtesy Of Ken Ikehara who should remain blameless!

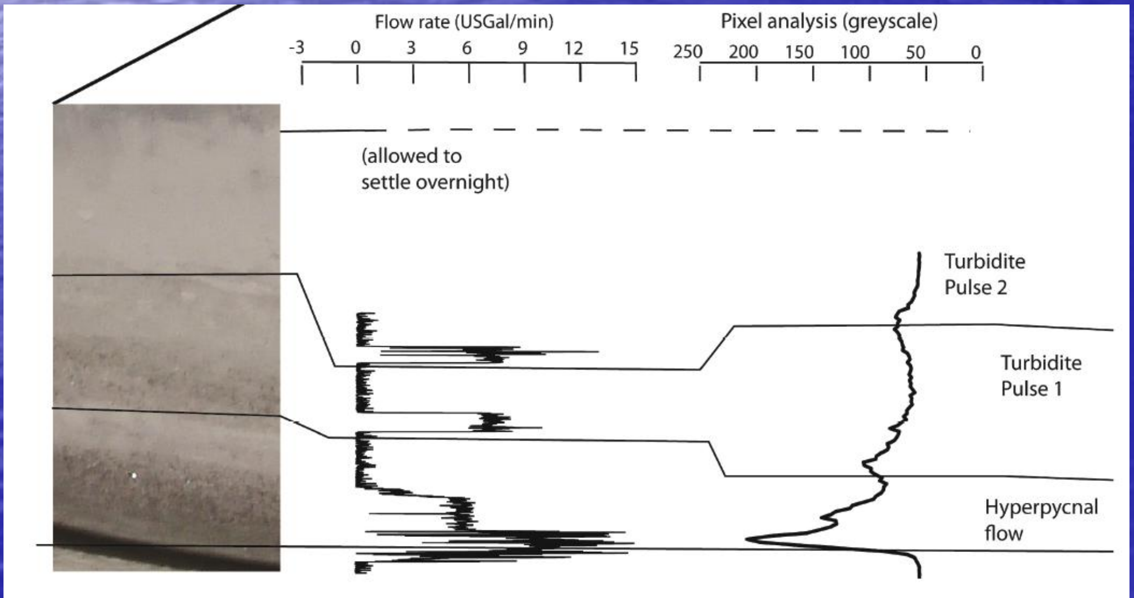


NEHRP supported flume experiments, in progress last 3 years.

Presented at AGU 2011, Garrett et al., 2011 (see our lab website), and NEHRP initial report available on the NEHRP website.

Testing recording of input sources in the sedimentary record.



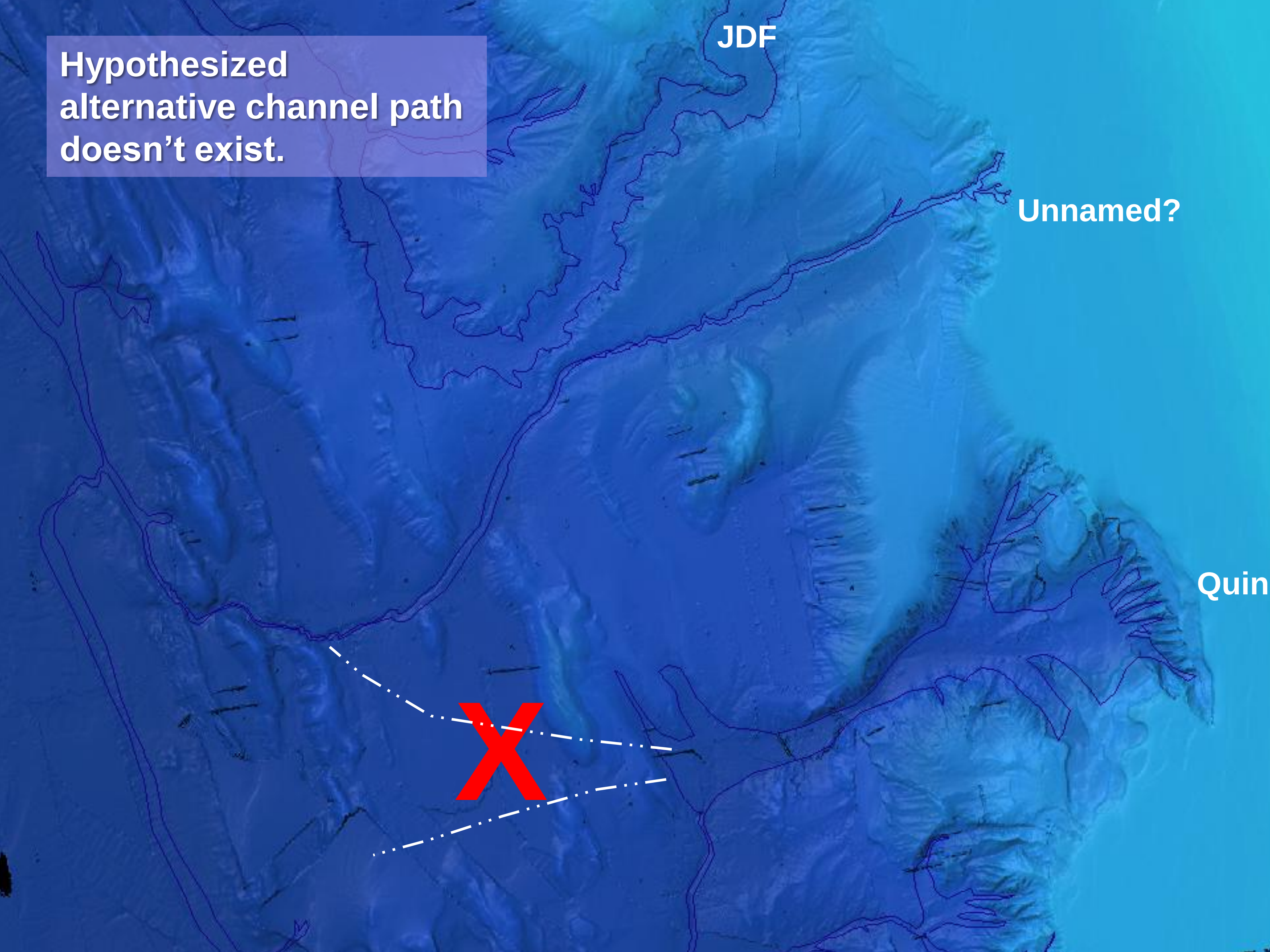


Theoretical and experimental analog results support the recording of input source heterogeneity by turbidite deposits.

Simulations include single and multipulse impulsive sources (earthquakes), and waxing and waning simulated hyperpycnal sources.

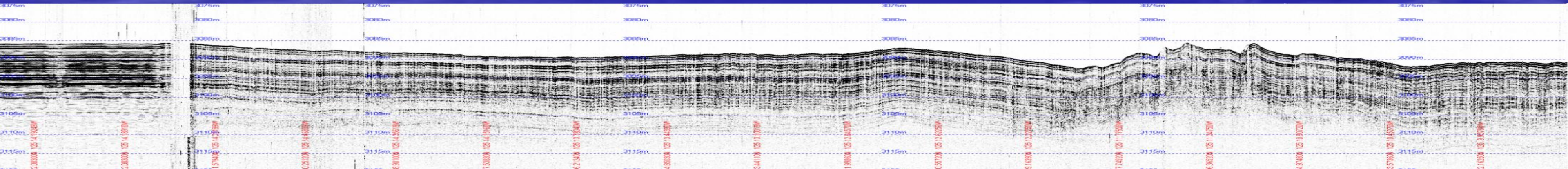
We vary all parameters, from slopes, to flow regime, to topography, to material and water density ratios. The results are essentially the same each time, the deposit reflects the flow hydrograph which overprints other secondary factors.


Questions?


Hypothesized alternative channel path doesn't exist.
JDF
Unnamed?
Quin
X

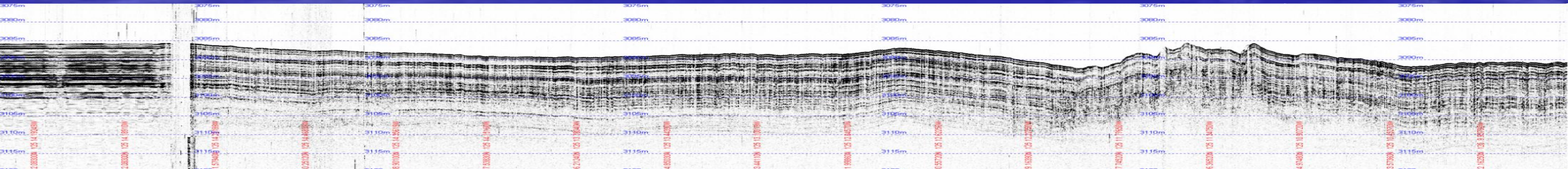
Response to Atwater Open File Report

- There is no evidence that JDF turbidites die on the way to the confluence. Considerable evidence to the contrary. Also there is no evidence for backfilling of JDF. Evidence of thinning is not evidence of attrition. Thickness changes and even non-deposition in some areas due to bypassing (hydraulic jumping) is not unusual particularly in channelized flows.
- There is not a likely alternative pathway from Quinault Canyon to JDF. This was recently remapped using 2011 Thompson multibeam data.
- Recent high resolution 3.5 kHz chirp data show that the abyssal plain turbidites in proximal areas are ubiquitous. Apparently they are delivered both as channelized flows and as sheet flows simultaneously. In a way this could render the confluence test moot, but the data also show very little variability, essentially replacing the confluence test with a better metric. Further work is required here!
- There is little if any problem with the 13 count of turbidites above the Mazama ash. We do not report that JDF core 05 PC has this count, erroneously stated in the report. There is no evidence for a "revised count" as hypothesized, though certainty is unobtainable with existing data.
- Complex turbidites are cited as potential evidence of additional events on the northern margin. This possibility always exists. Geologic variability is always present, we do not always know the reasons. But the vast majority of the evidence supports multi-pulse single turbidites.



Response to Atwater Open File Report

- Brian's several scenarios based on timing rest in part on a misunderstanding of the turbidite sources. Comparing travel times is more complicated than measuring the length of a channel and using a speed estimate. Currents are not solely sourced at the canyon head, rather the entire channel system is a line source, or an amalgamation of line sources. Timing is just not simple at all. We can't do it and we've been thinking about this for ~ 10 years. This is why there are no travel time models in the Professional Paper. What is needed is a much more sophisticated flow model that considers bathymetry, flow paths, ground shaking etc. Stay tuned…
- Geophysical correlation. This report builds on the above mistatements and misinterpretation of counts and flowpaths to say that "one channel feeds the other" to explain the excellent geophysical correlation. This is not the case.
- Unfortunately, casual cut and pasting of hard copy images of data is not adequate to evaluate correlations of core logs. Using the actual data is required, as is using modern flattening techniques that are the staple of the oil industry. The data are available for the asking. It's also best practice to incorporate all of the supporting data simultaneously. No one technique, whether it is geophysical logs, radiocarbon data, confluence tests etc. is likely to be the smoking gun. The correlations are variable in quality, ranging from so-so to remarkably good, but they do not stand alone. See Bayesian model.

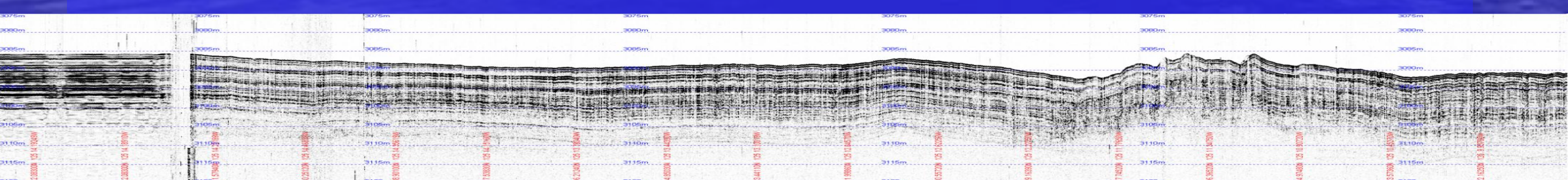


- “Paleoseismograms”. There can be no doubt that there are many reasons that a primary seismic shaking signal might be shredded by transport and deposition processes. We proposed this model to explain the data. In all we do, we use Bayesian methods to test a hypothesis given the data, not the other way around. Presently there is no working hypothesis that can explain this phenomenon other than seismic shaking. Arguing that it doesn’t exist because there are many things that could make it fail is not science. The remarkable consistency, and evidence from Chile, Sumatra and San Francisco suggest that this hypothesis is one that holds promise in the case of the largest earthquakes.

- Radiocarbon ages. Brian incorrectly states that the methods do not include error propagation for the age averages, this is not correct, they are fully incorporated. Further, the best ages are provided as OxCal “combines” of the same data. All Oxcal combines pass the X2 and A comb test of synchroneity (at the resolution of 14C of course). Arbitrary doubling of errors is not justified for eroded intervals.

- The report states that “very little is known about the rates of deposition in lower Cascadia Channel” Actually those rates are the best known, with large numbers of older cores in the area, and shown in PP 1661-F figure 48, and in Table 5. The uncertainly there is quite small. Increasing the error ranges is therefore not justified.

- Coring disturbances can and do cause variability in estimates of thickness of anything in the cores, including hemipelagic. However we have tried to carefully avoid disturbed units in our cores whenever possible.



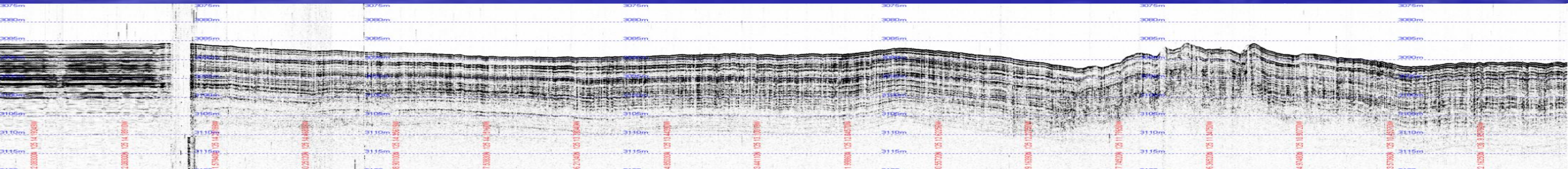
- Serial ruptures.
- Brian states that the expectation that there should be serial ruptures "trumps the evidence" against them.   Actually there is little evidence for them, or any "expectation" (whatever that is) in Cascadia.   We have assessed the hypotheses given the evidence, nothing more. We have not yet found much evidence pointing to serial ruptures, but it may well be there and it wouldn't be that surprising. The probability of this hypothesis, given the data as we have it today, is low. However, that could change in the future.

- We agree that the Bradley evidence for one case of serial rupture may be real. We have evidence from offshore and now from lakes that support that interpretation. T16 may also be a serial rupture, more work is needed. So far, that's all we can see, but again, this could change with new evidence.

- Otherwise, the strong lithostratigraphic support a high probability of 19 (of 43) long ruptures.

- Mud turbidites offshore are not consistent with storms or dam breaching, they are present at hydrate ridge, and also do not have the sedimentological content or structure of such flows.

- The separation of T2 into two events is possible, but unlikely given the strat correlation, strong radiocarbon series and hemipelagic estimates of time intervals. Bioturbation is not a valid indicator of time, but it's not needed in any case due to good radiocarbon.

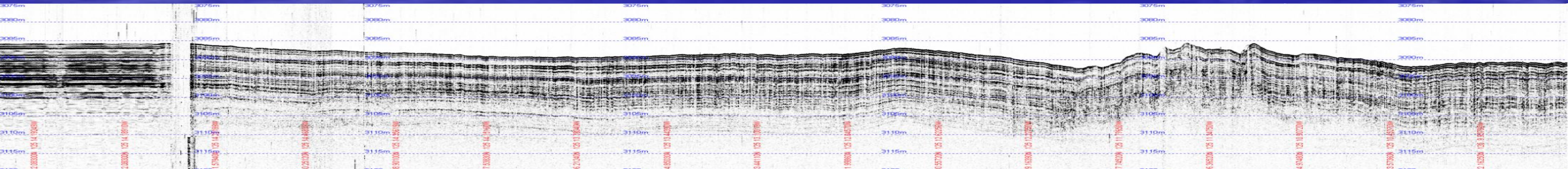


- Despite an abundance of literature, and long discourse on this subject in 1661, the report ignores decades of literature to state, yet again, that bioturbation is a useful indicator of time. It's just not so. Much of the literature is cited in 1661. We commonly observe individual *Zoophycus* burrows sweeping through meters of the same core. If it worked, we'd be using it.

- Energy cycling. The report relates old concepts that relate years of plate convergence to the size of the earthquake, combined with timing from bioturbation, to argue for an alternative scenario for T2. There is really little reason to try to make this relation directly given recent evidence from Tohoku (M 9 earthquake after only a few decades!). But, it's commonly done due to lack of information of long term patterns. It's dubious at best, and best avoided with present knowledge.

- Many of the improvements to this line of work suggested in the report have been underway for a number of years, and are incorporated in new papers. Unfortunately, because of the rather glacial production schedule, USGS 1661-F has been "in press" for 3 years now.

- Suggestion to work with more sedimentologists. Advice to the authors, please check out the people in the author list, many of them are career sedimentologists, and are highly offended by such cavalier comments.



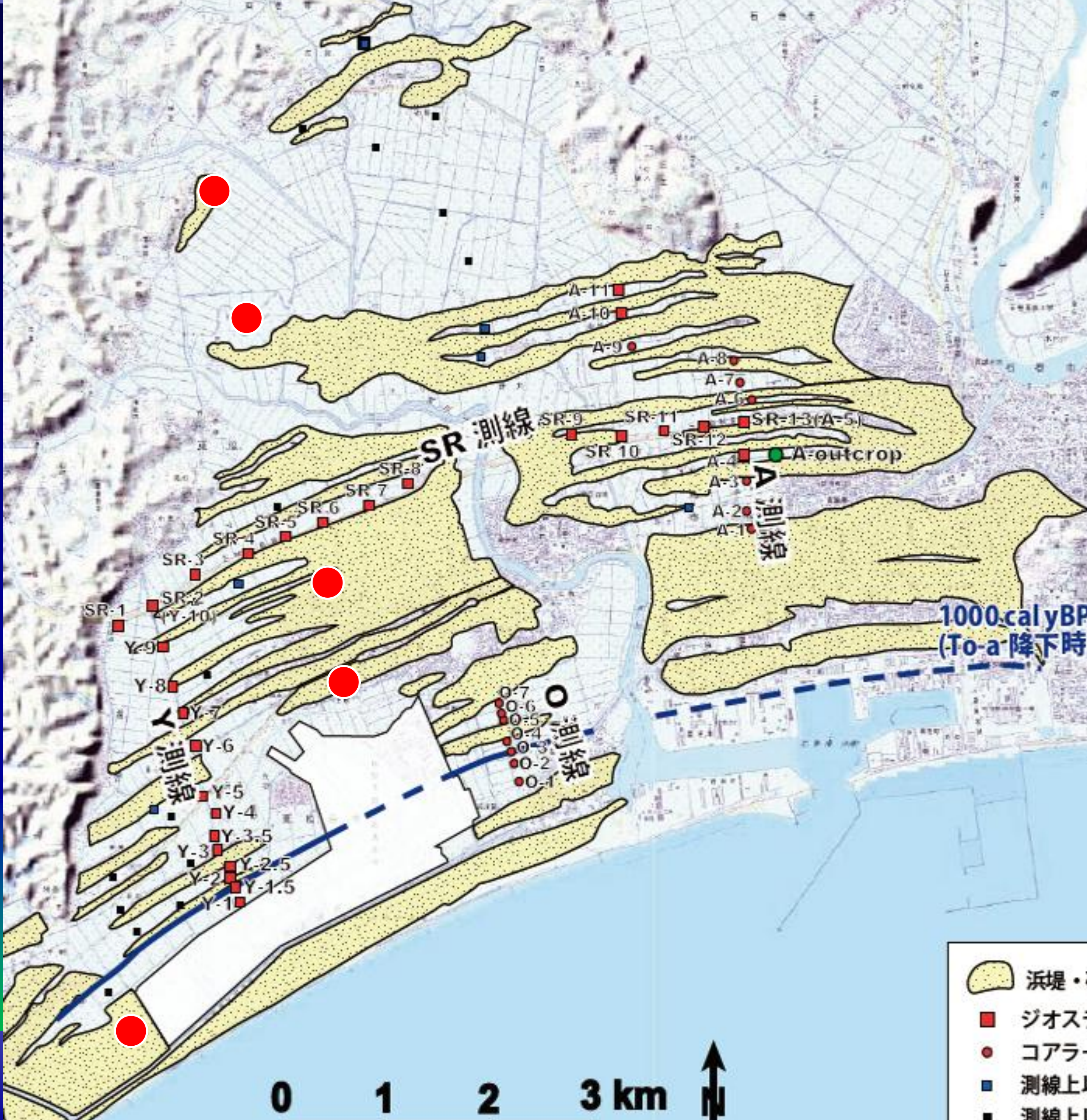
Let's take a little detour to Sendai….

Japan was well prepared for earthquakes and tsunami. Why was the tsunami still so devastating despite extensive preparation and education?

The reason fundamentally is that the Japanese were well prepared, but for the *wrong earthquake*.

They expected and planned for what the historical record and seismological theories predicted, an ~ 8.4 earthquake.

Ruff and Kanamori, a widely applied model for subduction zones relating plate age and convergence rate predicted a mid Mw=8 maximum for NE Japan and may other zones with old subducting plates. This theory had begun to come apart in recent years, but it's demise was signaled by Tohoku. It doesn't work.

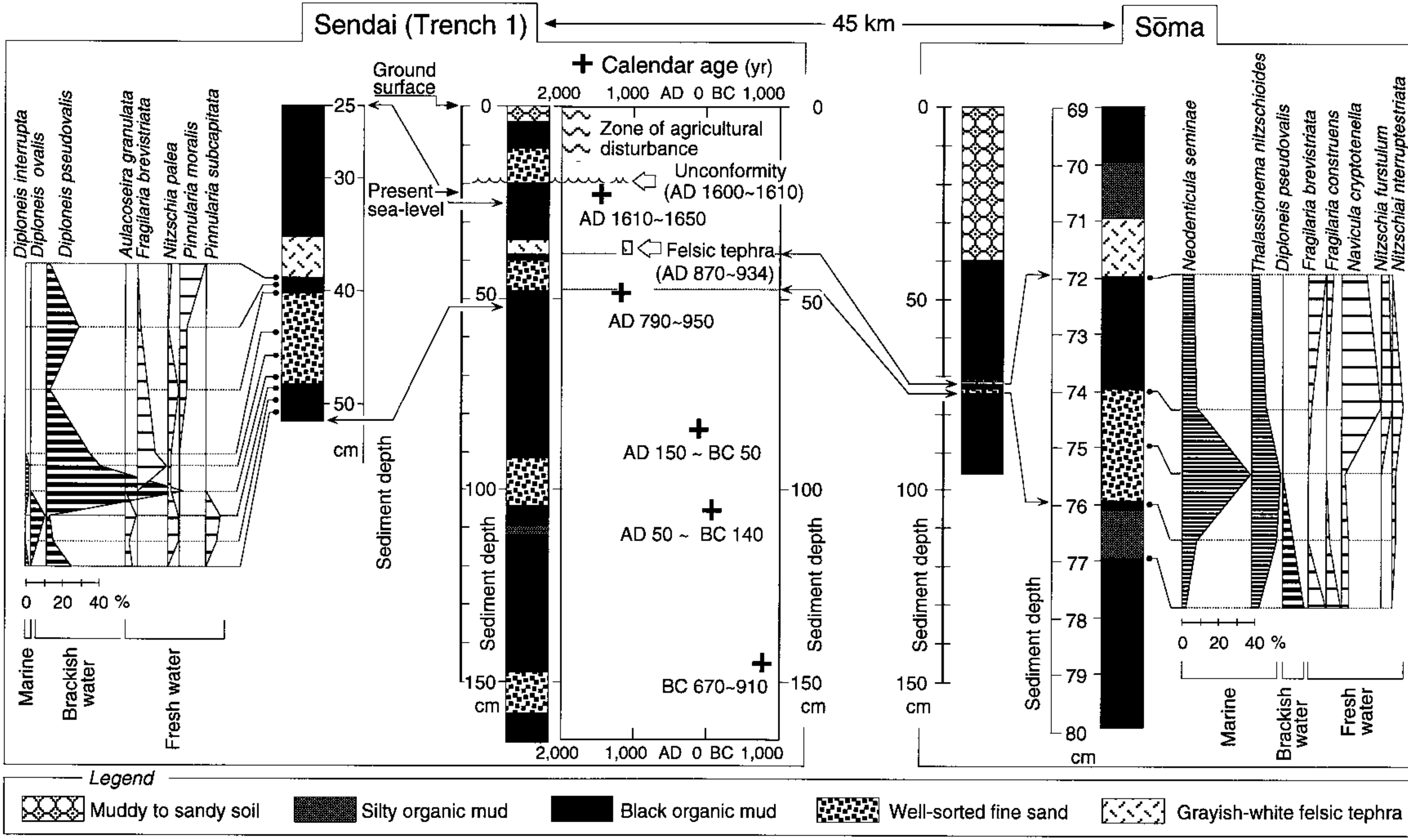


869 Jogan tsunami inundation (From Shishikura et al., 2007).

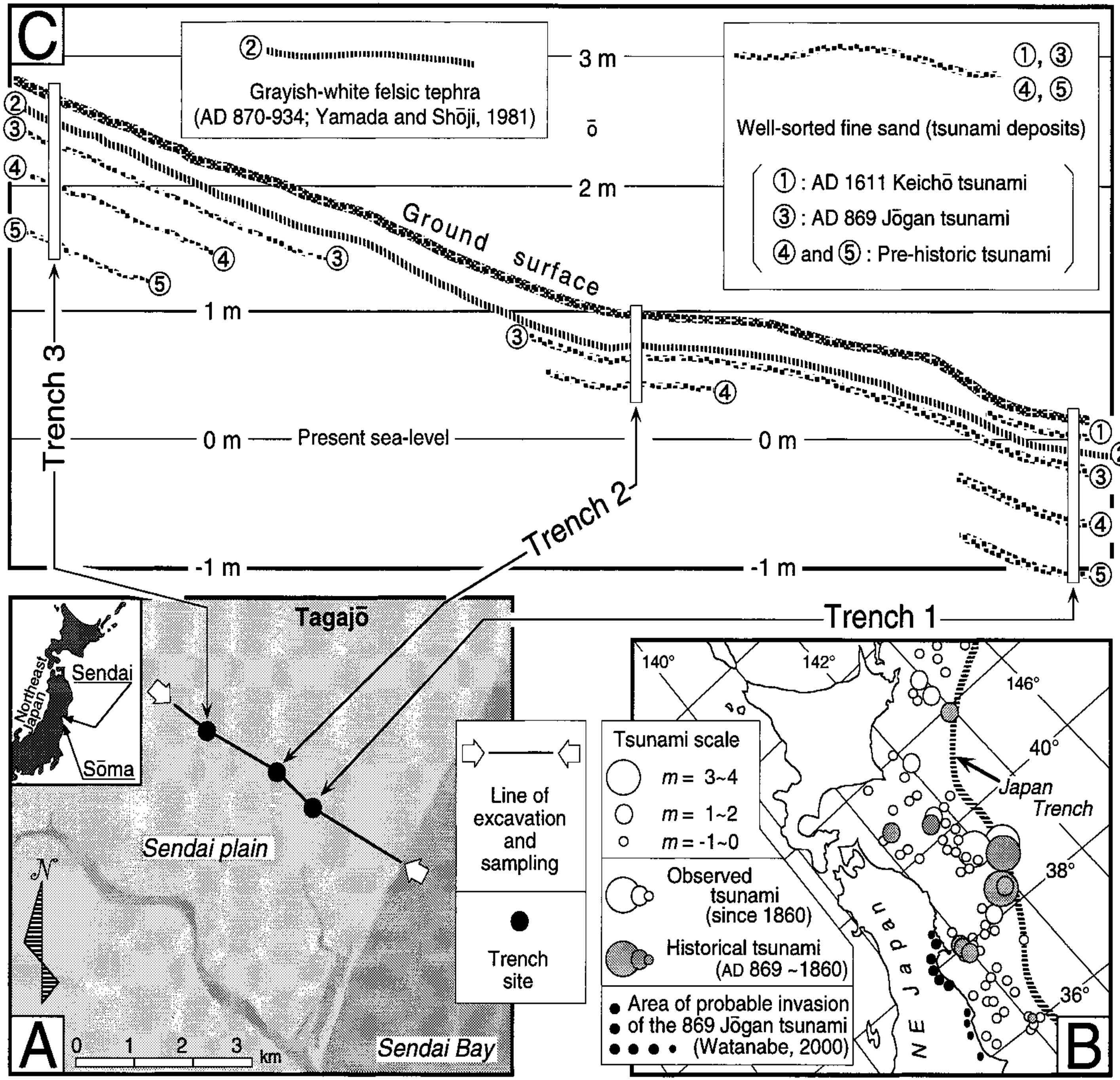
We trenched at the 5 red dots, and confirmed and added to this analysis.

We also found that the Jogan tsunami was at least locally much larger than 2011!!

Figure S1. Tsunami pit transect across the Ishinomaki plain. To examine the robustness of the AD 869 Jogan tsunami inundation we dug five shallow pits across the Ishinomaki Plain west of Ishinomaki. White line indicates approximate coast in in Jogan time. Red line indicates approximate limit of discernable deposition from the 2011 tsunami. Blue line indicates approximate limit of inundation from the 2011 tsunami. This area was also investigated by Shishikura et al. (23) who show Jogan deposit distribution on the Ishinomaki plain.

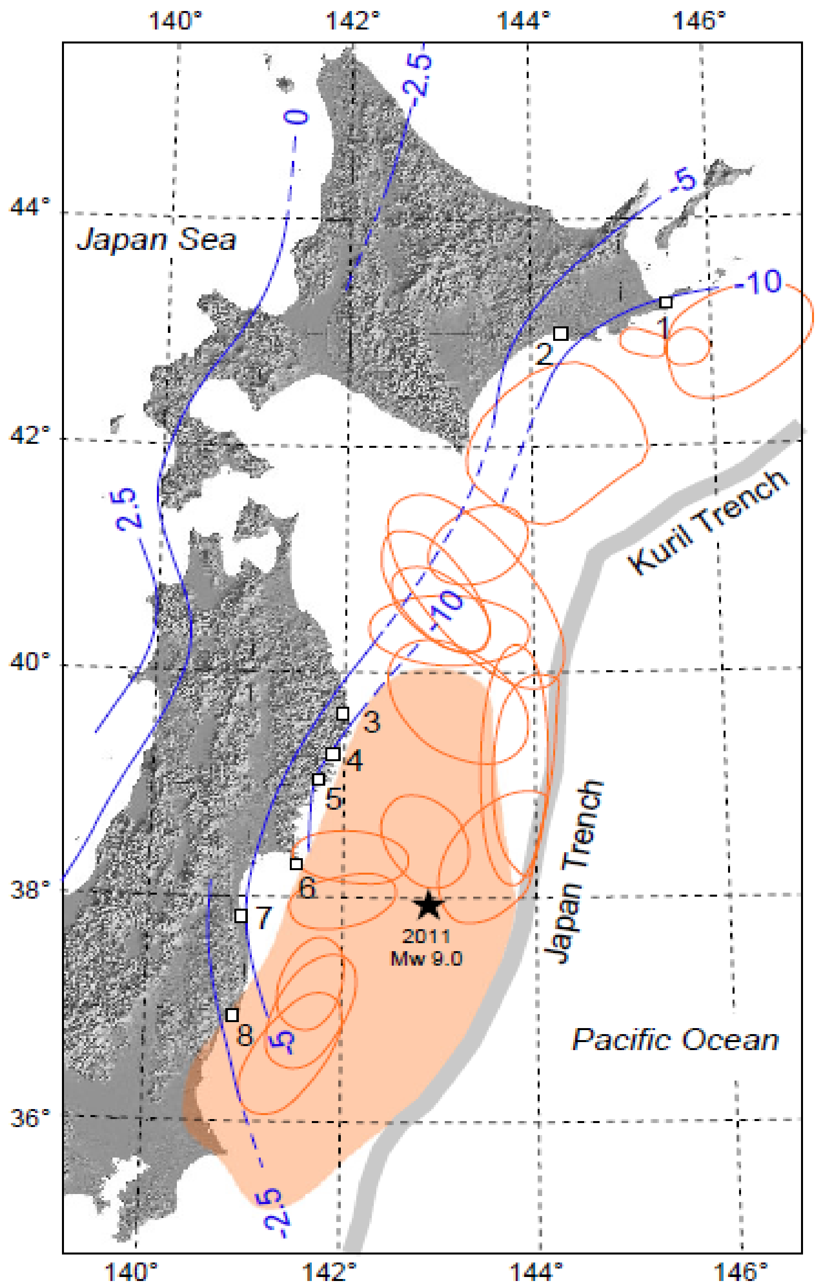


Core data from the Sendai plain with Jogan and two predecessor tsunami, with the stratigraphic records tied together by a tephra layer just above the Jogan tsunami deposit. Recurrence interval of these extreme events is ~ 1000 years (from Minoura et al., 2001)



Evidence that the 869 AD Jogan tsunami and two predecessors penetrated ~ 4 km inland in the Sendai plain, compared to < 1 km for more recent events was published in 2001 by Minoura et al.

Additional work by Sawai et al., 2007 ,2008 and Shishikura et al., 2008 confirmed this result. Even considering coastline shift of ~ 1 km seaward since Jogan time, this was likely a much larger event than any other in the historical record



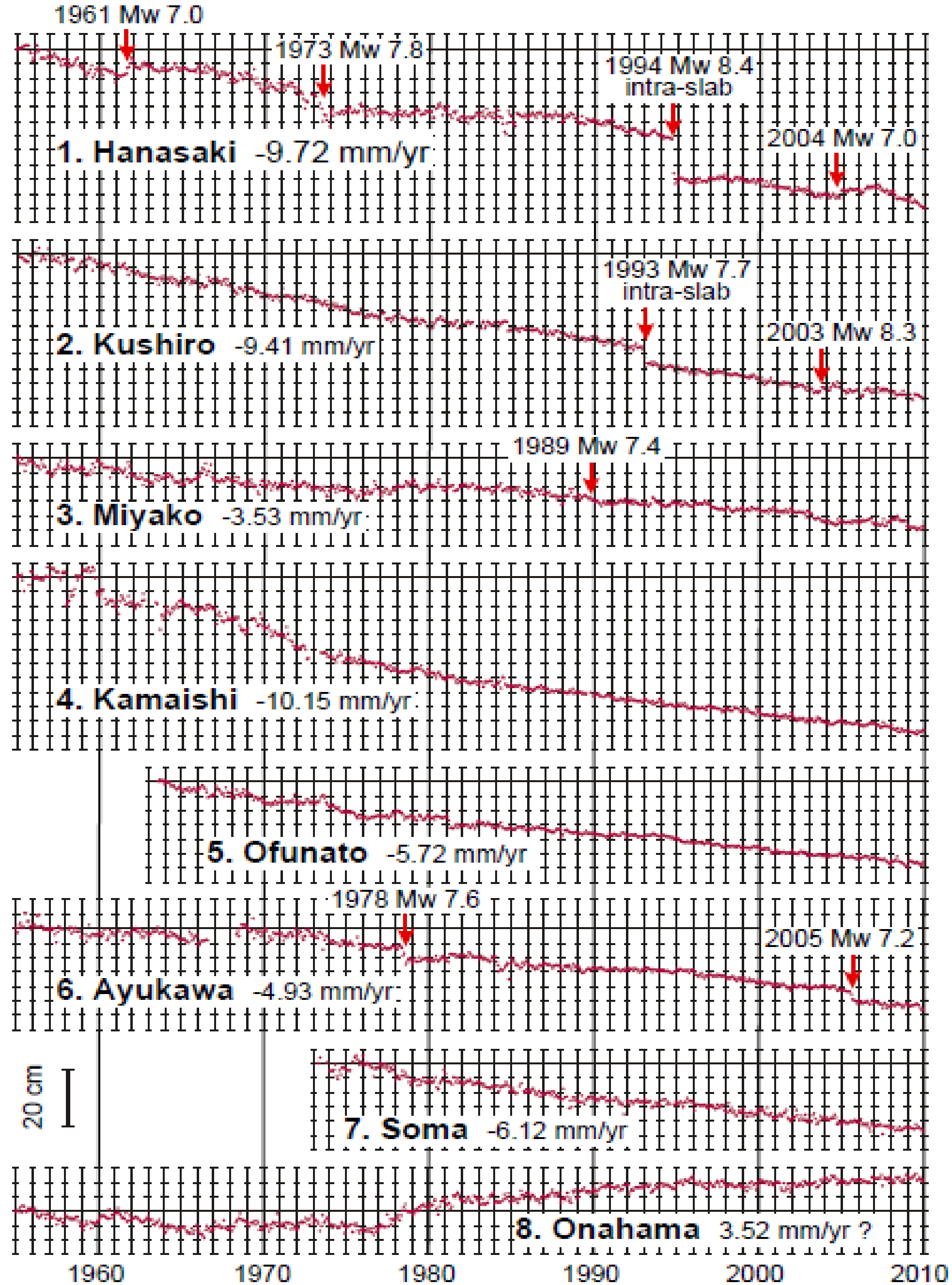
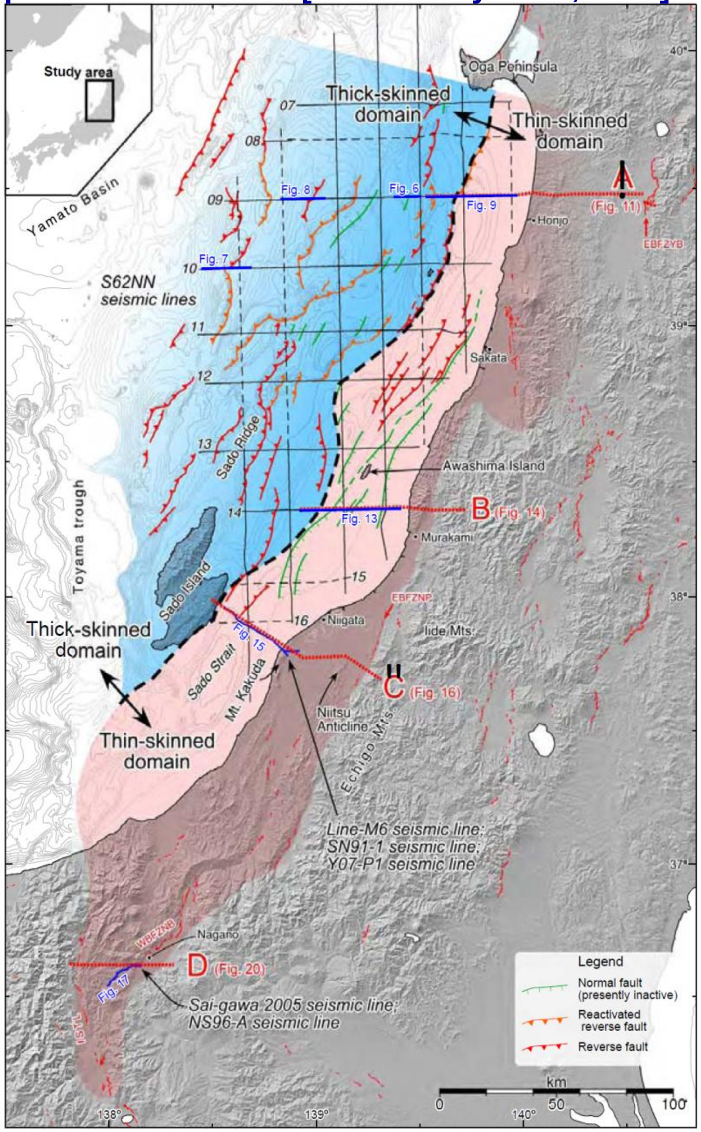


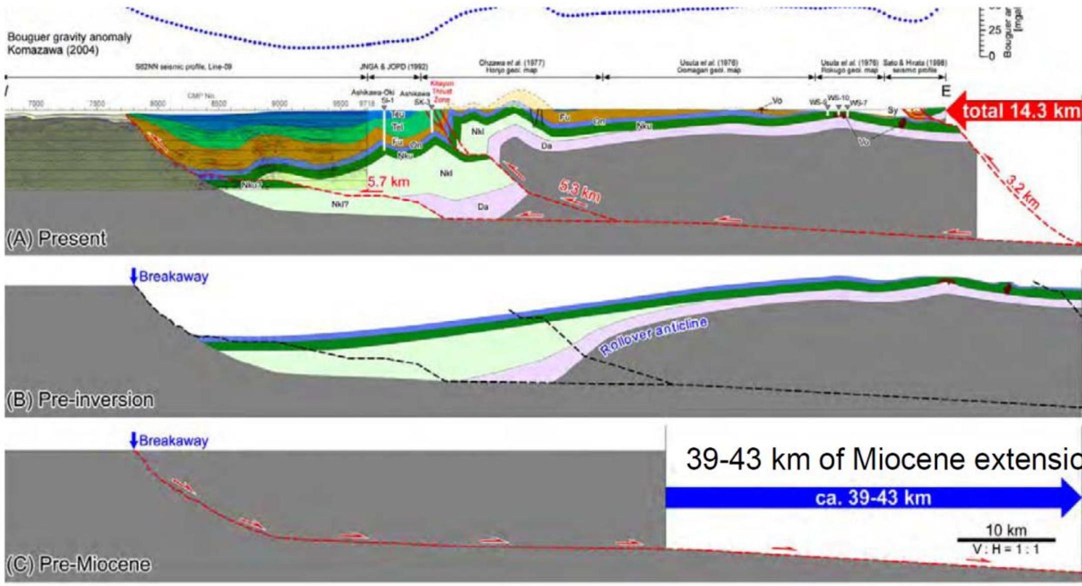
Figure from Goldfinger, Ikeda, and Yeats, submitted.

Shortening across the Uetsu fold and thrust belt is ~3-5 mm/yr. [Okada and Ikeda, 2011]. Including other active faults and folds, the rate of horizontal shortening over the Northeast Japan arc is estimated at 5-7 mm/yr, in good agreement with previous estimates [Wesnousky et al., 1982].

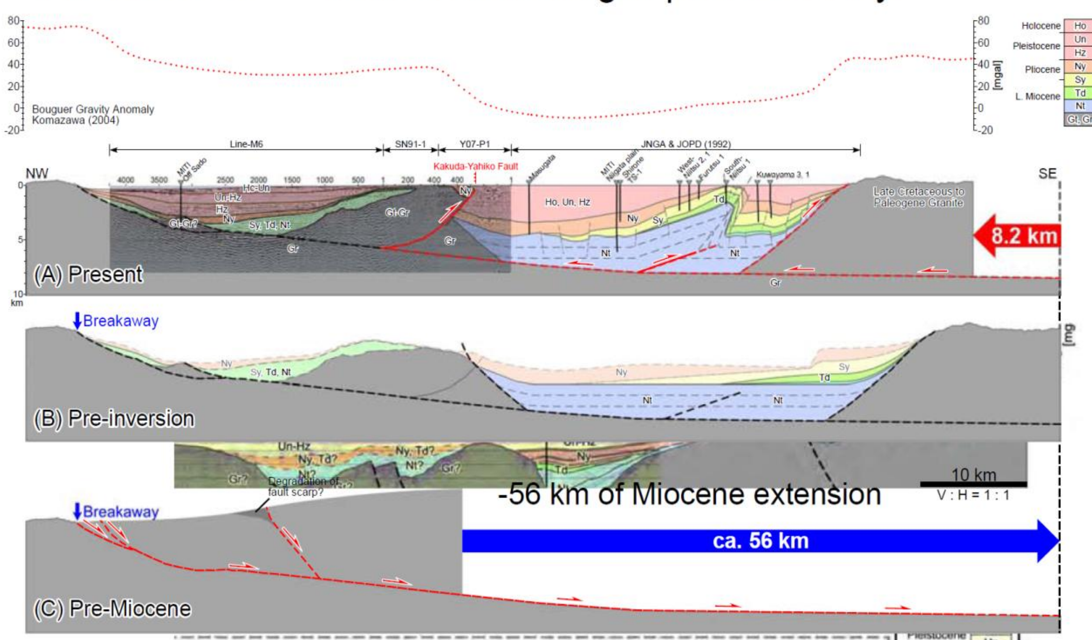


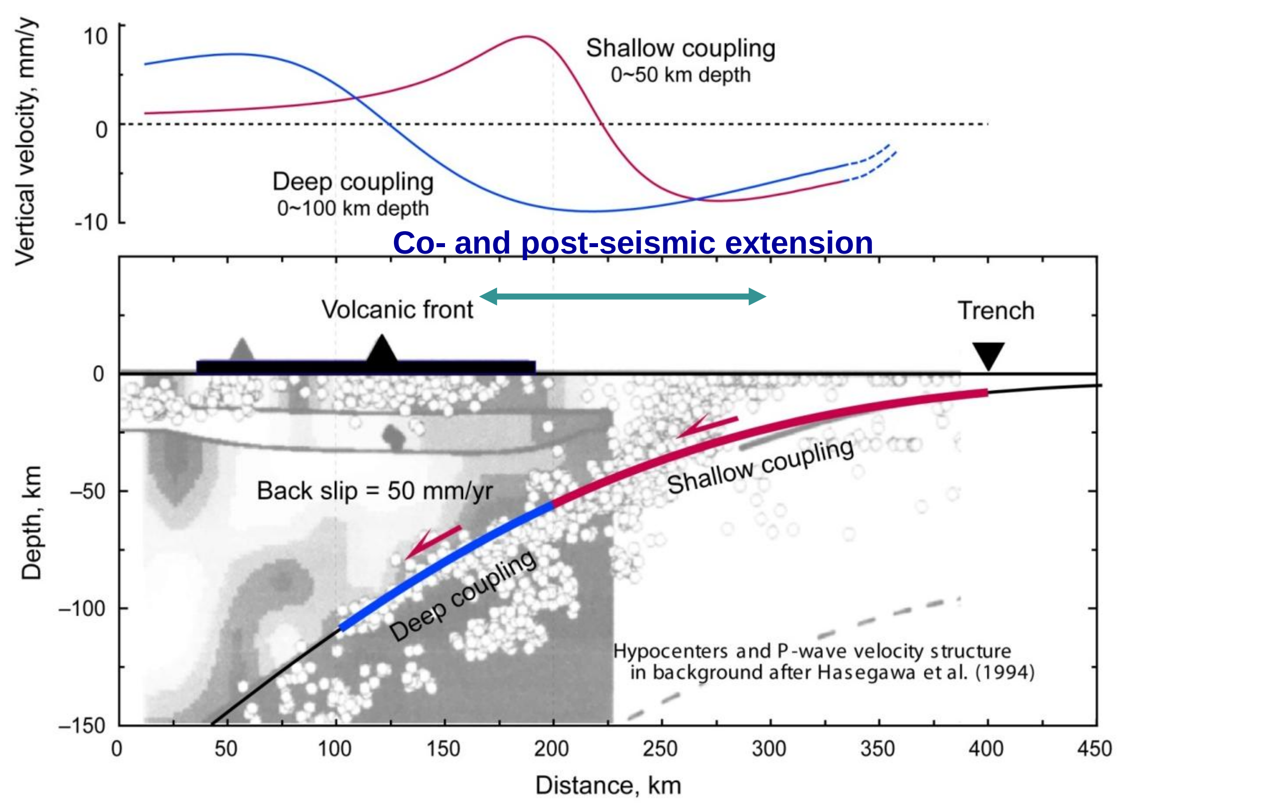
Okada and Ikeda, 2011, *JGR* (under review)

Transect A: 14 km of shortening in past 3.5~5 Myr



Transect C: 8 km of shortening in past 3.5~5 Myr





Vertical velocity, mm/y
10
0
-10
Shallow coupling
0~50 km depth
Deep coupling
0~100 km depth
Co- and post-seismic extension
Volcanic front
Trench
Depth, km
0
−50
−100
−150
Back slip = 50 mm/yr
Shallow coupling
Deep coupling
Hypocenters and P-wave velocity structure
in background after Hasegawa et al. (1994)
0
50
100
150
200
250
300
350
400
450
Distance, km

Conclusions

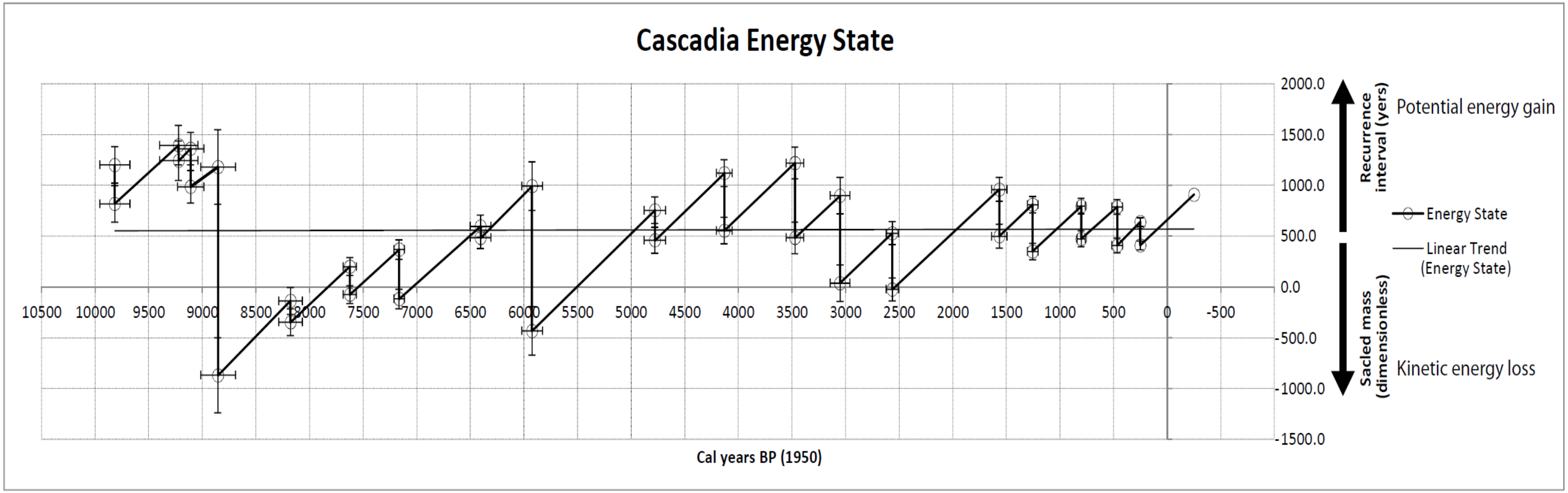
• We have NOT observed a whole cycle of strain buildup and release in NE Japan arc (or subduction zones in general) by geodetic methods.

• Most of the strain (both horizontal and vertical) accumulated in the past 100 years at an abnormally high rate is elastic, and ***will be released in association with a big decoupling event (Mw ~9) on the subduction zone.***

• Only a fraction (< 10%) of plate convergence will be accommodated within the arc as long-term (and inelastic) deformation.

Concluding slide, Y. Ikeda, COE workshop, 2006

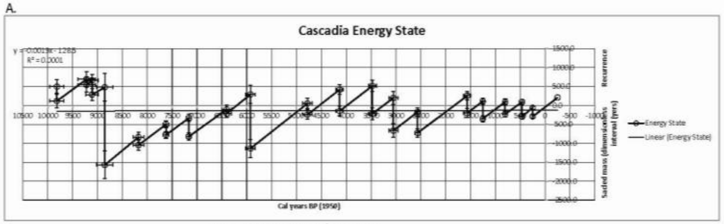
If we only knew the magnitudes of the paleoearthquakes, we might be able to figure out what was going on…



In this plot we arbitrarily scale Cascadia turbidite mass (energy loss) against recurrence time (energy gain), setting the slope of the trend = 0 to maintain a long term constant state. The resulting plot suggests long term energy cycling that is neither time nor slip predictable, but does appear to have some periodicity.

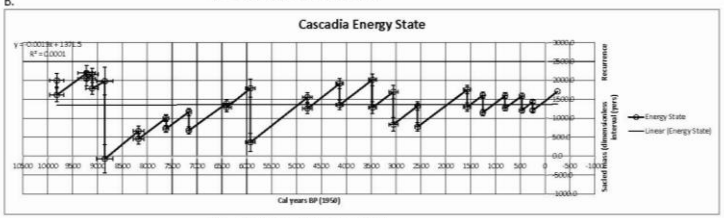
The pattern is fairly robust, observed at all sites, and probably not an artifact of the simple model

A.



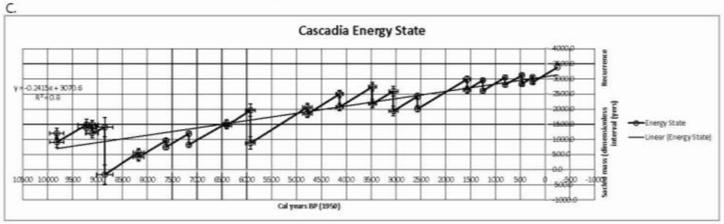
SF = 13150, start value = 500

B.



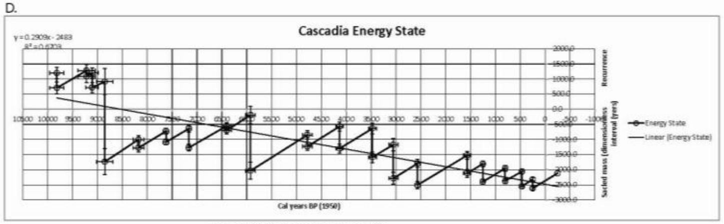
SF = 13150, start value = 2000

C.



SF = 10000, start value =1200

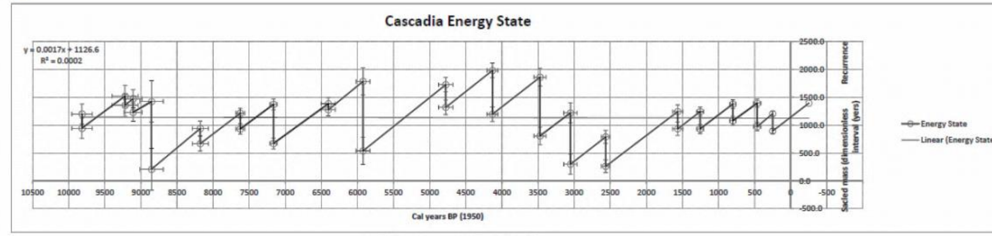
D.



SF = 17000, start value =1200

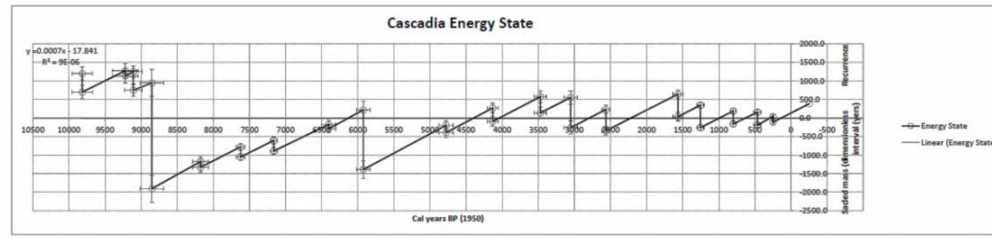
The pattern is not sensitive to the starting value (upper 2 panels). Other scale factors change the slope of the energy plot, which is possible at long time scales, but the general pattern remains evident (lower two panels).

A. **JDF Channel**



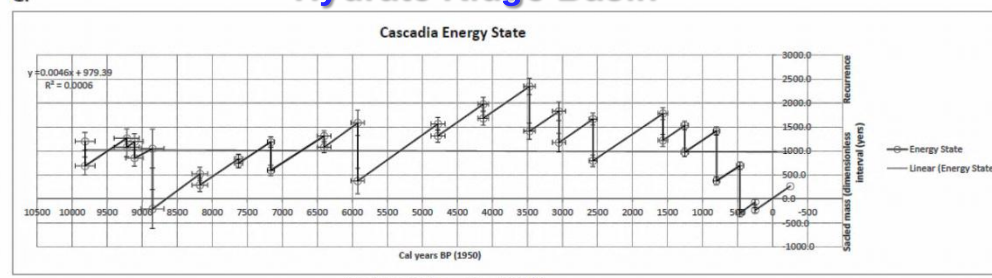
Juan De Fuca: SF = 13200

B. **Cascadia Channel**



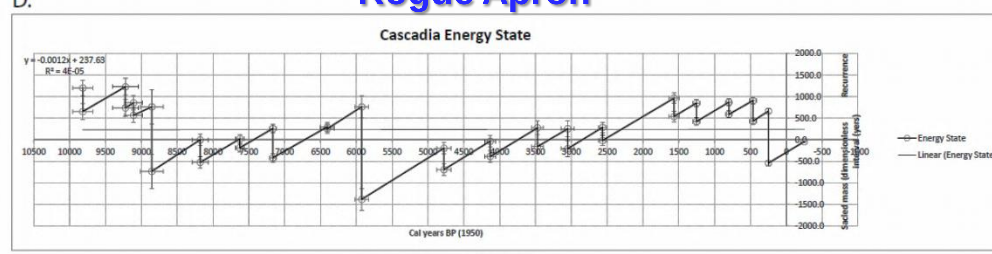
Cascadia: SF = 13550

C. **Hydrate Ridge Basin**



Hydrate Ridge: SF = 15540

D. **Rogue Apron**



Rogue Average: SF = 16100

Holocene energy state plots for all four key core sites, Cascadia margin.

The history of shallow thrust earthquakes in the region did not match the large elastic strain indicated by GPS and tide gauges, and were only offset slightly by permanent strain across NE Japan.

Forecast of M9 earthquake by Ikeda-san in 2003, also presented in Hokudan in 2005, was based on this mismatch.

Later, tsunami deposits confirmed the presence of outsized tsunami including the 869 Jogan and two similar predecessors at ~ 1000 year intervals.

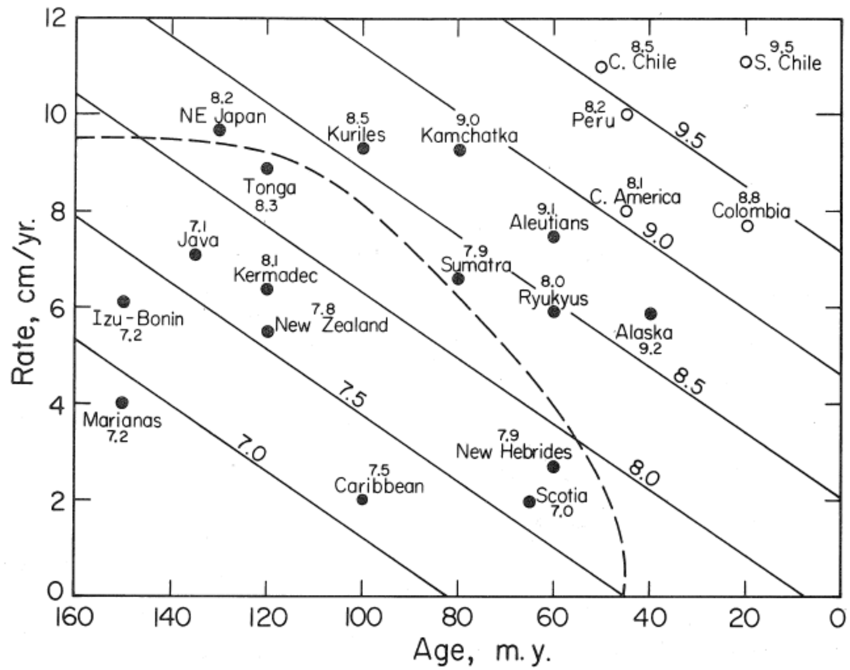
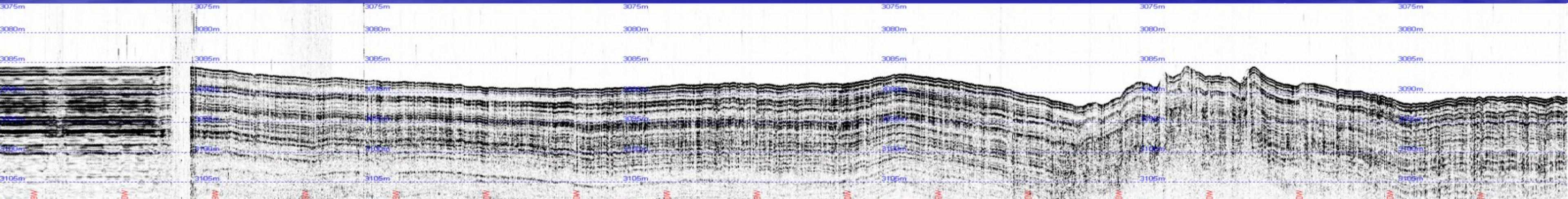


Fig. 3. As Fig. 2 except that the South and Central American points are not included in the regression analysis. The remaining 16 subduction zones conform quite well to the regression plane.

The well known and often taught model of Ruff and Kanamori (1980) failed because you can't capture fault behavior with only 100-200 years of data. Obvious now, but not in 1980.

Conclusions

- **Segmentation of the Cascadia margin is robust from offshore and onshore paleoseismology, and may be consistent with ETS segments.**
- **Northern margin conditional probabilities are similar (~ 12% in 50 years) to previous estimates. Reliability analysis places the northern margin at ~ 25^{th} percentile after 360 years. Southern margin probabilities are ~ 37% in 50 years. Reliability analysis places the southern margin at ~ 80^{th} percentile after 360 years.**
- **Clustering is likely present. On the southern margin, clustering is in the form of "moment clusters" if not in the strict temporal sense.**
- **Segmentation may be a function of sediment supply in both Cascadia and Sumatra (i.e. Ruff, 1985)**
- **We may be able to extract information about past earthquake ruptures from the turbidites themselves: "paleoseismograms"**

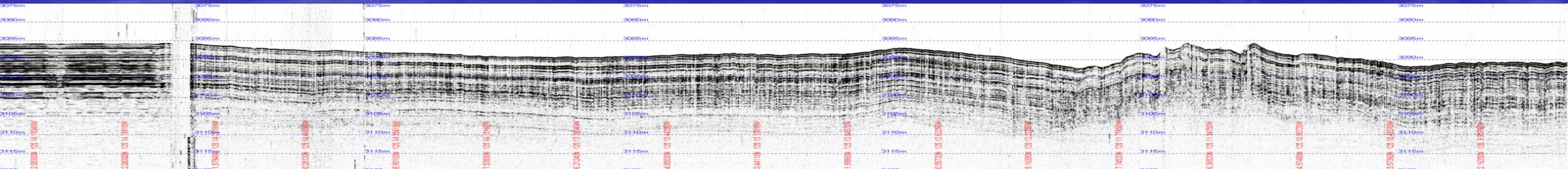


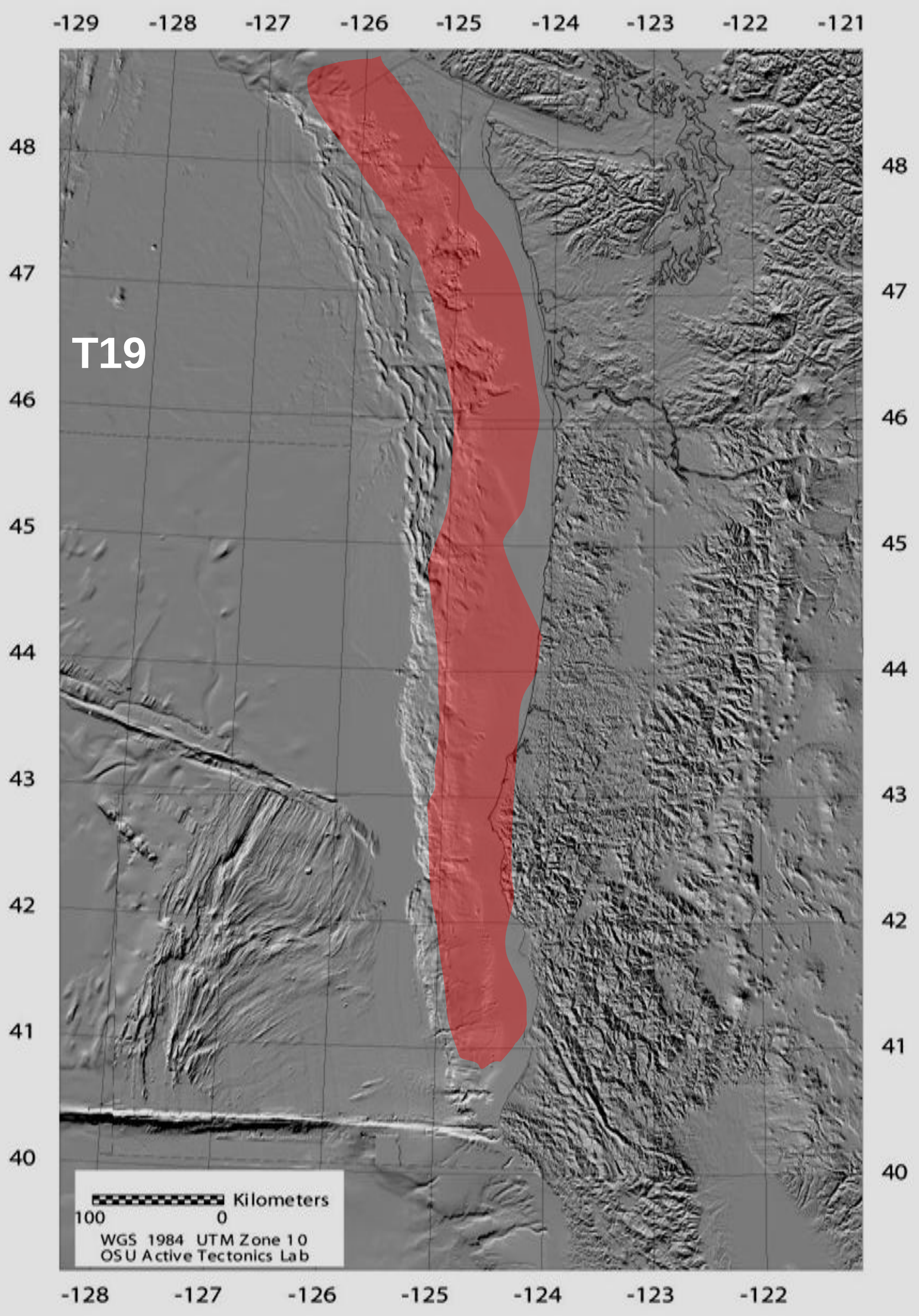
Conclusions

- Very long paleoseismic records have the potential to illuminate segmentation, clustering, probabilites, and the maximum considered earthquake (MCE), as well as reveal long term strain patterns i.e. “Supercycles”.
- Very favorable physiography and large numbers of samples in broad spatial context are required to develop long records with a high level of confidence.
- “Superquakes” occur in many fault systems, and may have very long recurrence times, ~ 1000 years in Tohoku, 3-6000 years in Cascadia, 6000 years on the Haiyaun fault (China).

Implications for Global Hazards

The failure of predictive seismological and geophysical models is substantially due to short time windows of observation. We must consider locations such as Java, New Zealand, Peru, Northern Chile, Barbados and many other localities as possible sites of future M9 earthquakes.



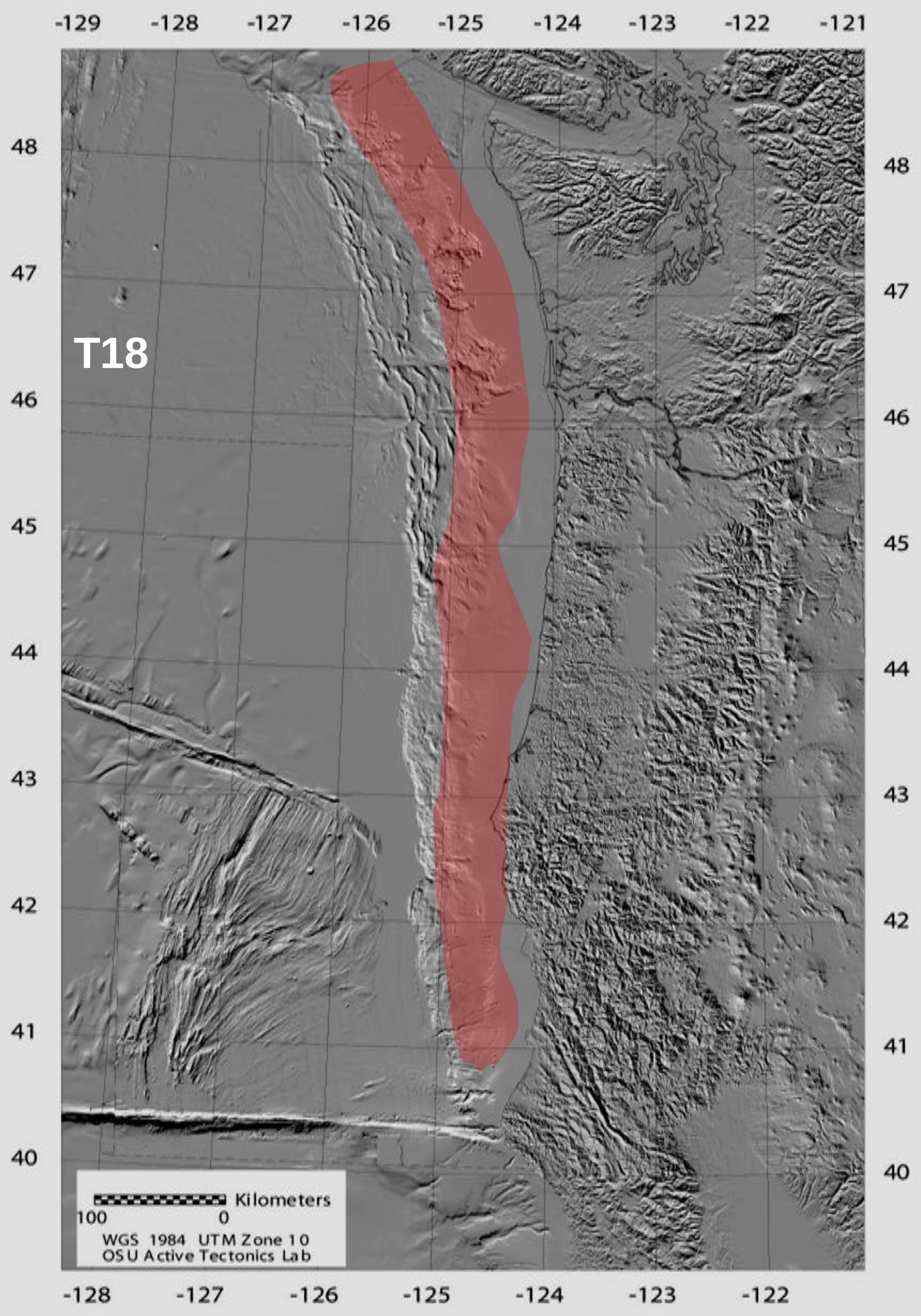


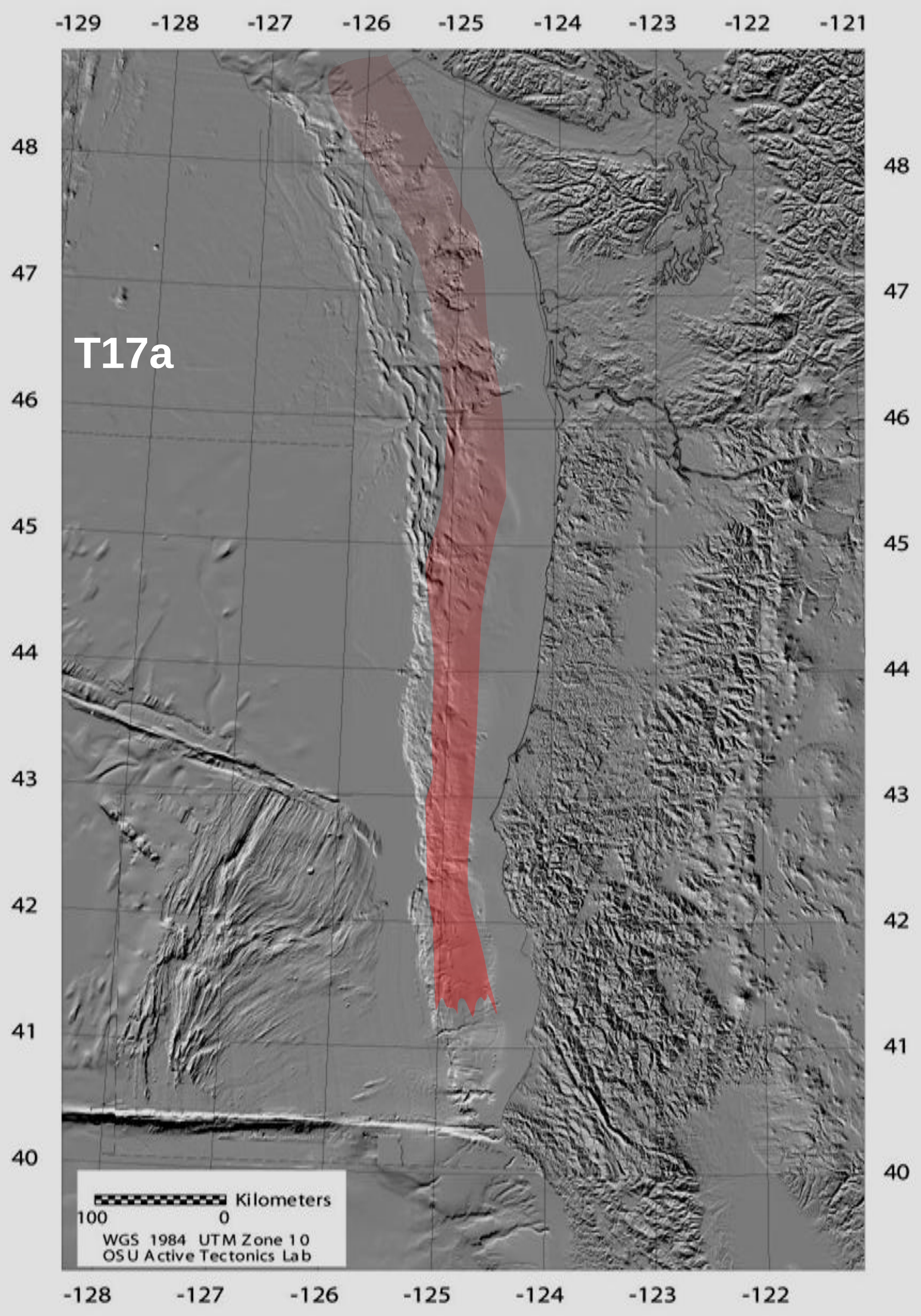
Cascadia: The Movie

This sequence shows the Cascadia Holocene earthquake sequence.

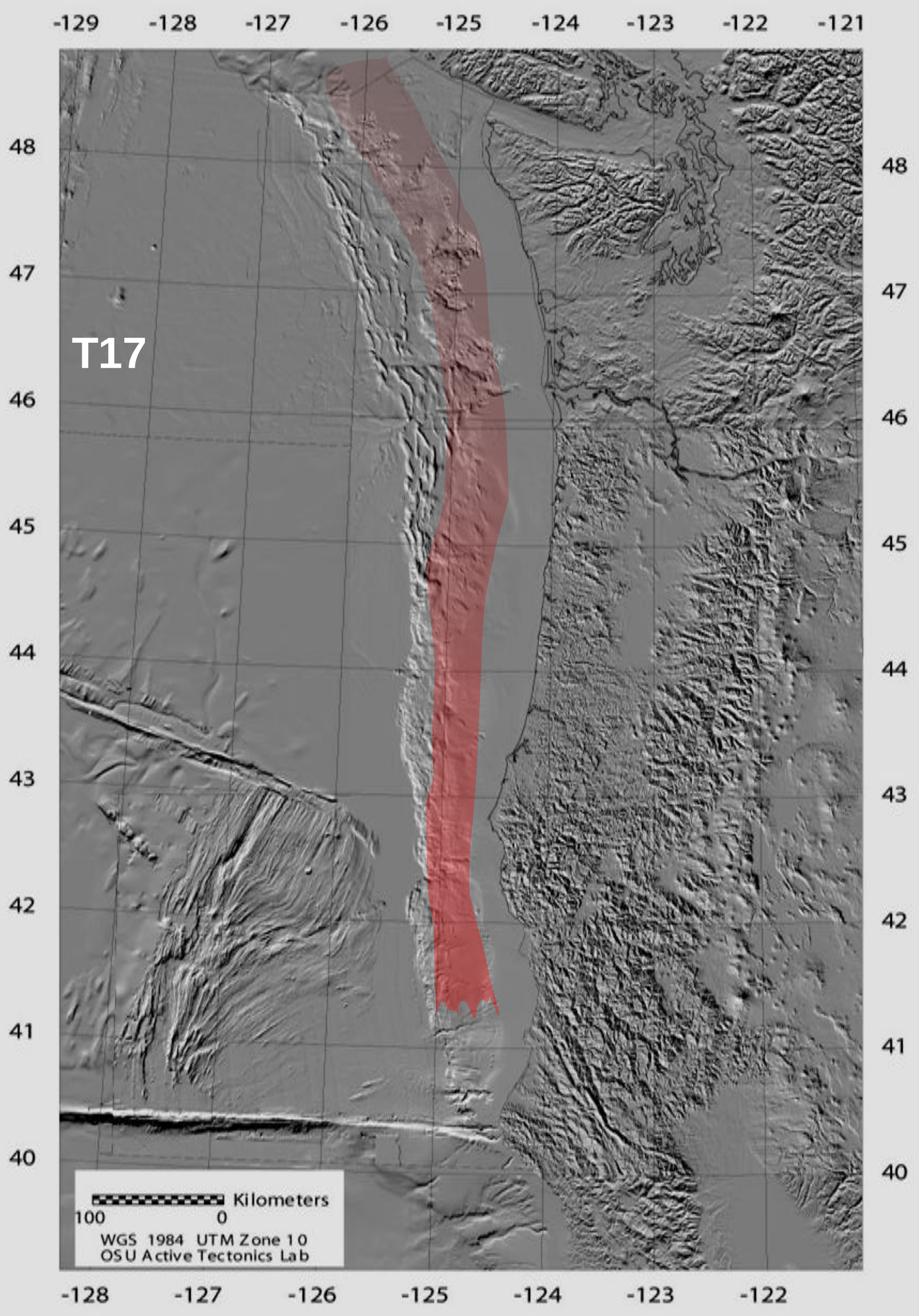
The slides are timed at 1 sec ~ 200 years.

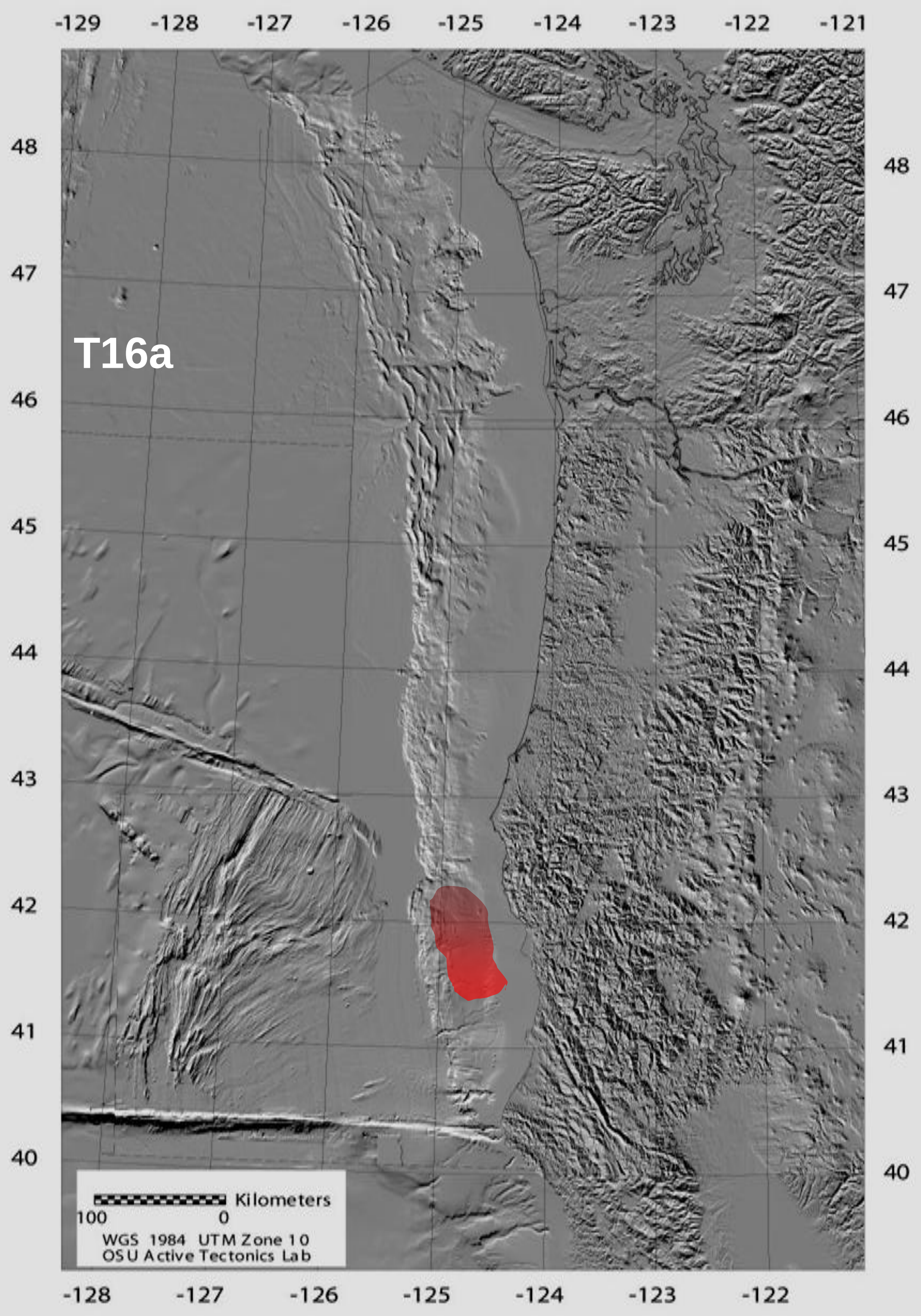
Event pulses that correlate at all sites are shown by flashes of the "locked zone" in red. Event "size" shown by intensity of red shading

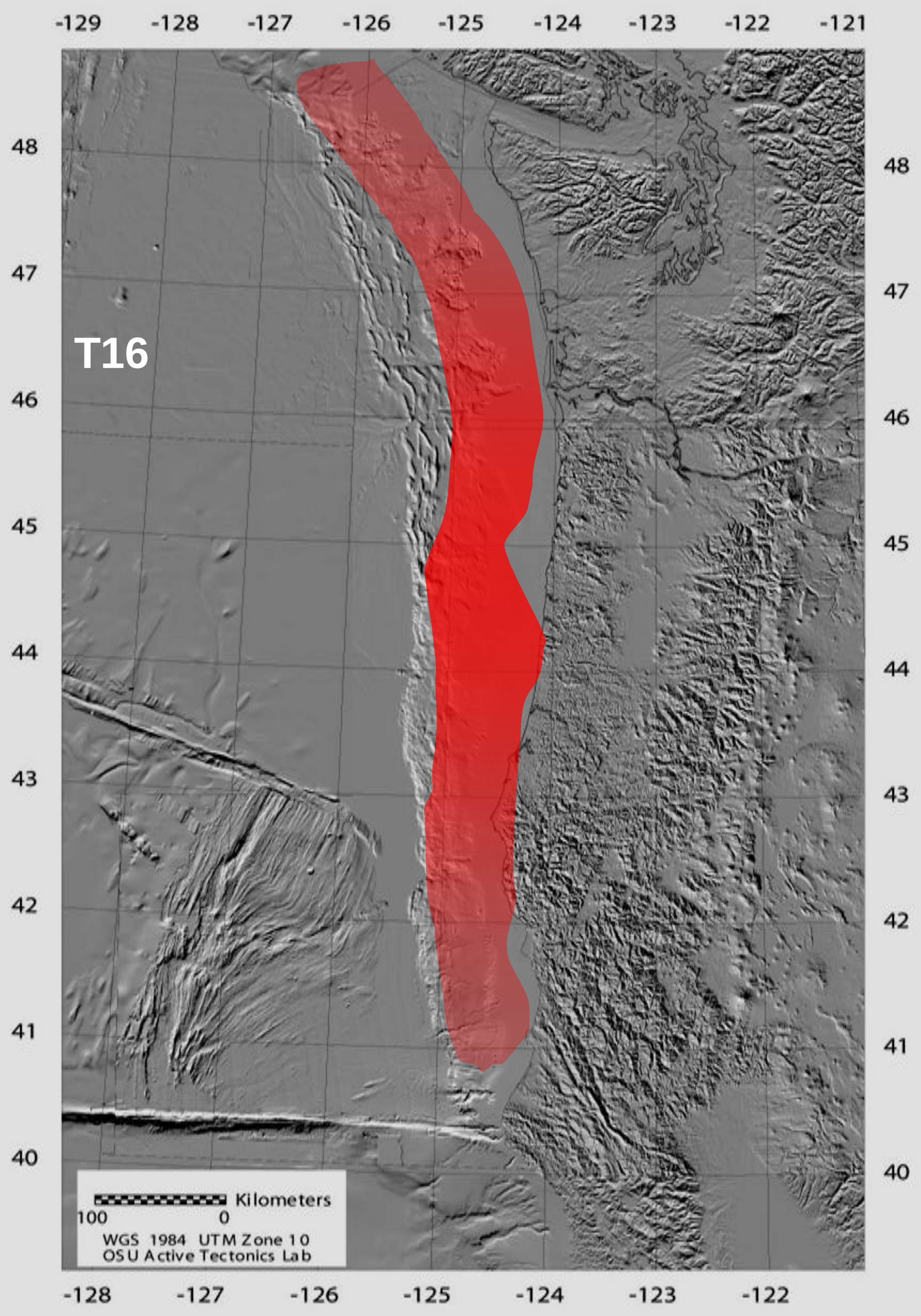

T18
Kilometers
100
0
WGS 1984 UTM Zone 10
OSU Active Tectonics Lab



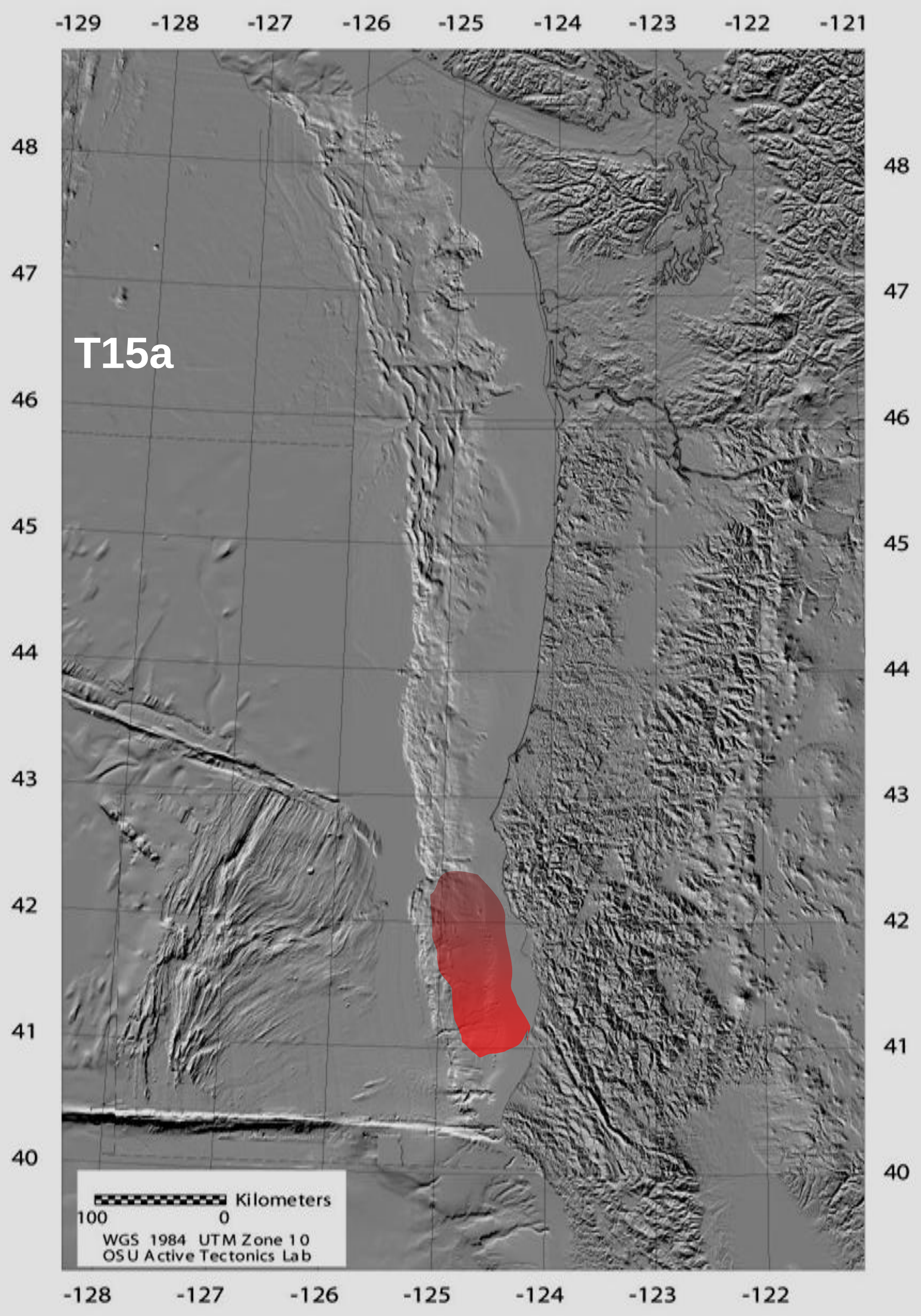
T17a
Kilometers
100 0
WGS 1984 UTM Zone 10
OSU Active Tectonics Lab
-129 -128 -127 -126 -125 -124 -123 -122 -121
48 47 46 45 44 43 42 41 40


-129 -128 -127 -126 -125 -124 -123 -122 -121
48
47
T17
46
45
44
43
42
41
40
Kilometers
100 0
WGS 1984 UTM Zone 10
OSU Active Tectonics Lab
-128 -127 -126 -125 -124 -123 -122

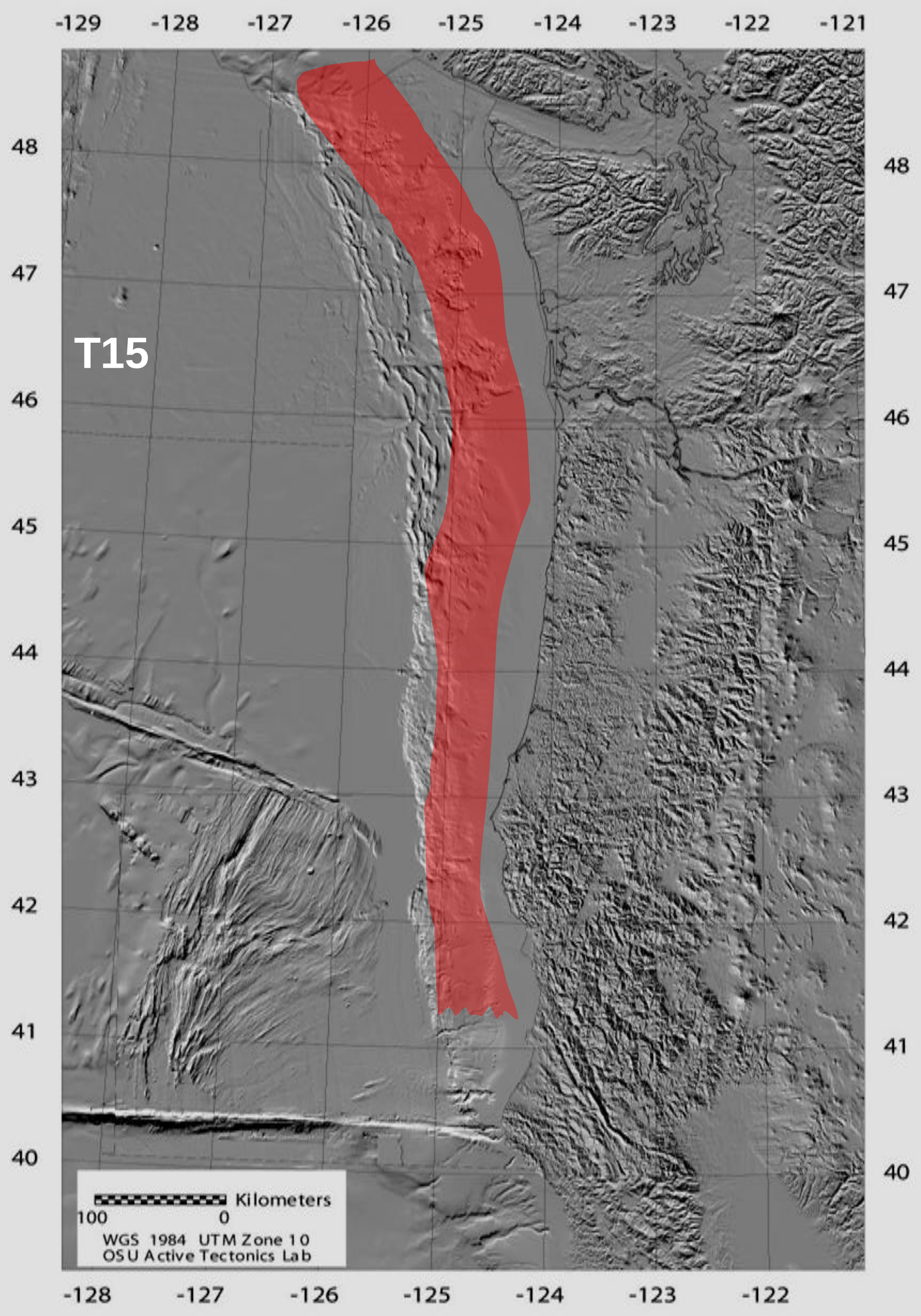

-129 -128 -127 -126 -125 -124 -123 -122 -121
48 47 46 45 44 43 42 41 40
T16a
Kilometers
100 0
WGS 1984 UTM Zone 10
OSU Active Tectonics Lab
-128 -127 -126 -125 -124 -123 -122



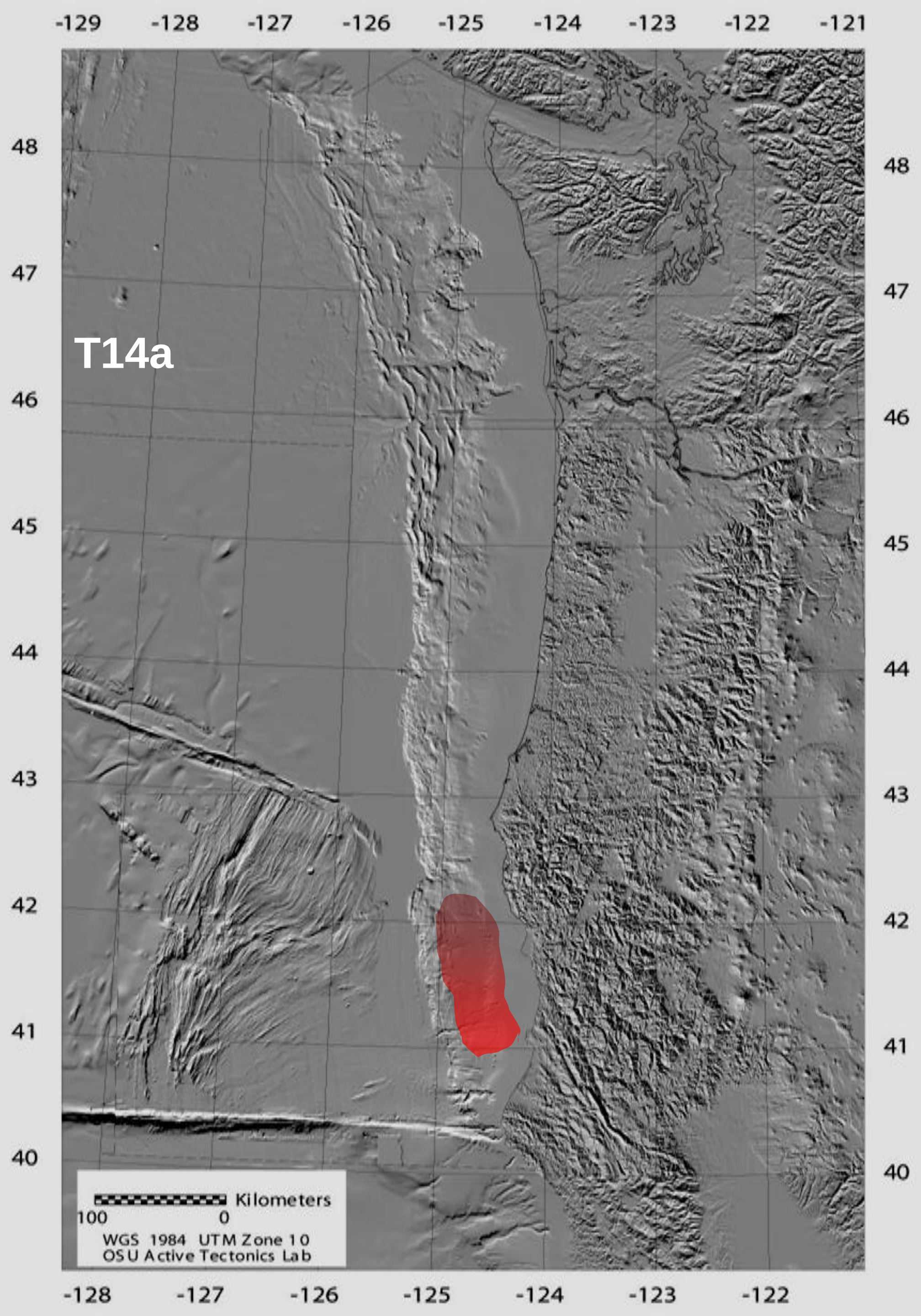
-129
-128
-127
-126
-125
-124
-123
-122
-121
48
47
46
45
44
43
42
41
40
T16
Kilometers
100
0
WGS 1984 UTM Zone 10
OSU Active Tectonics Lab

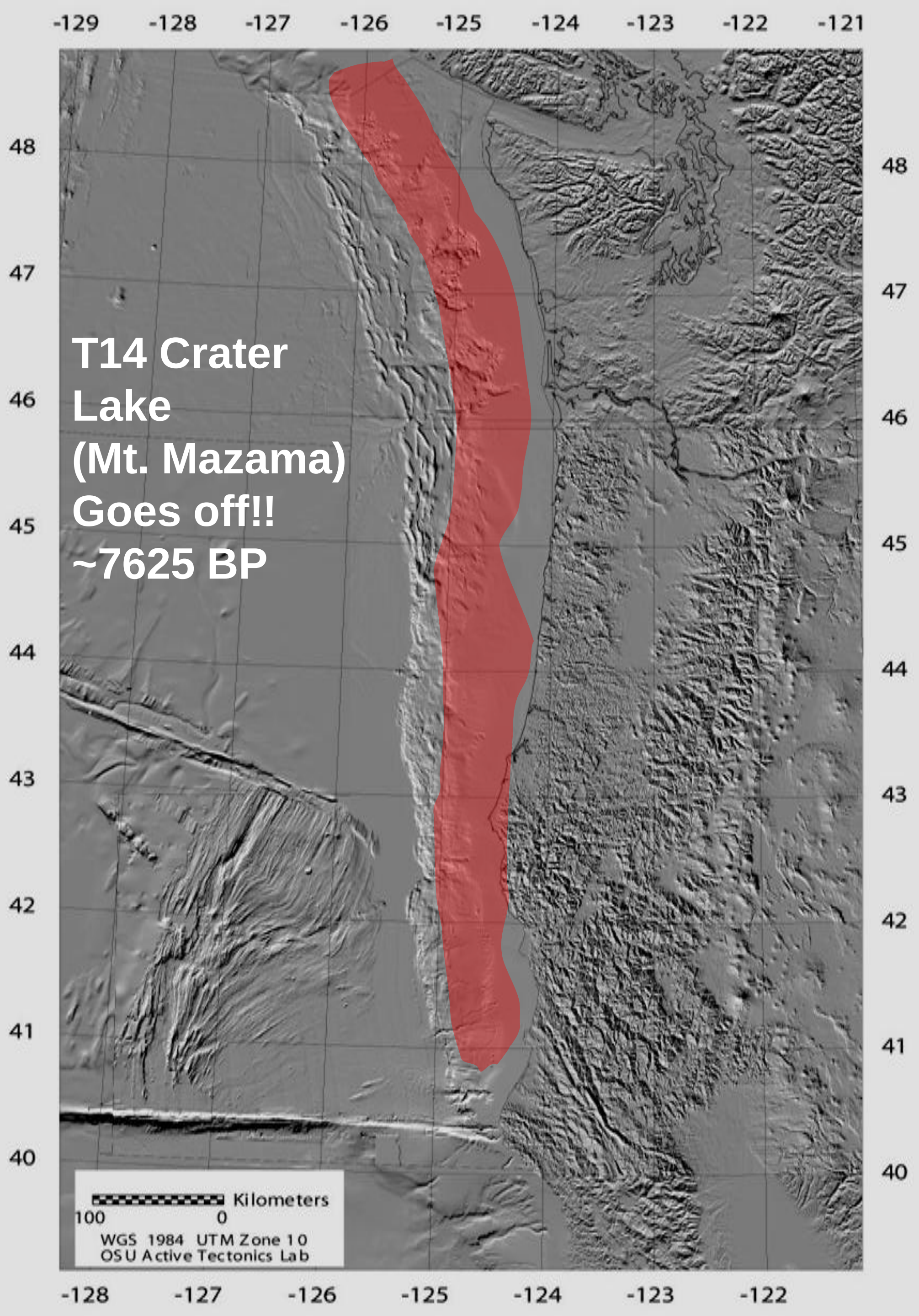


T15a
-129 -128 -127 -126 -125 -124 -123 -122 -121
48 47 46 45 44 43 42 41 40
-128 -127 -126 -125 -124 -123 -122
Kilometers
100 0
WGS 1984 UTM Zone 10
OSU Active Tectonics Lab

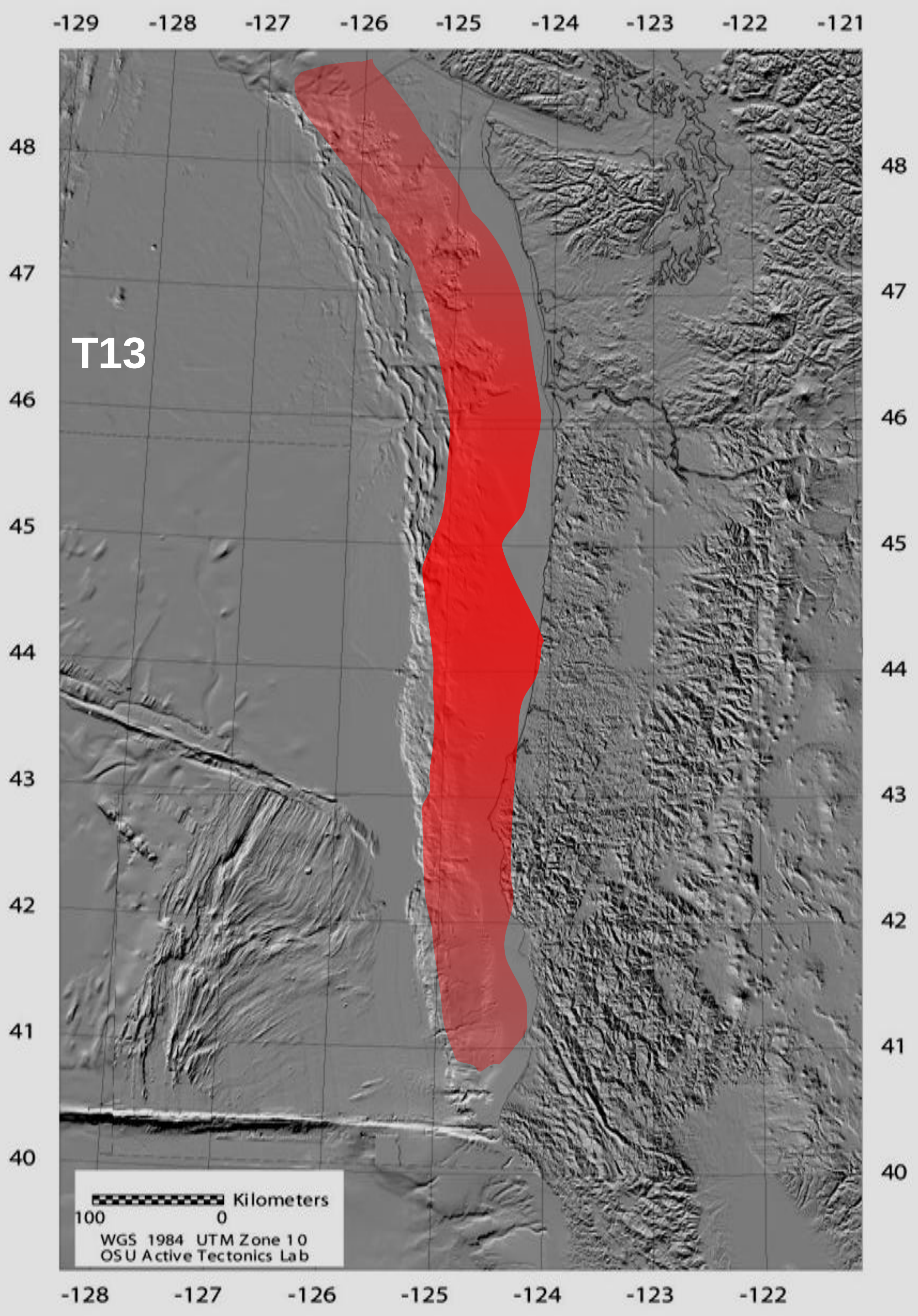


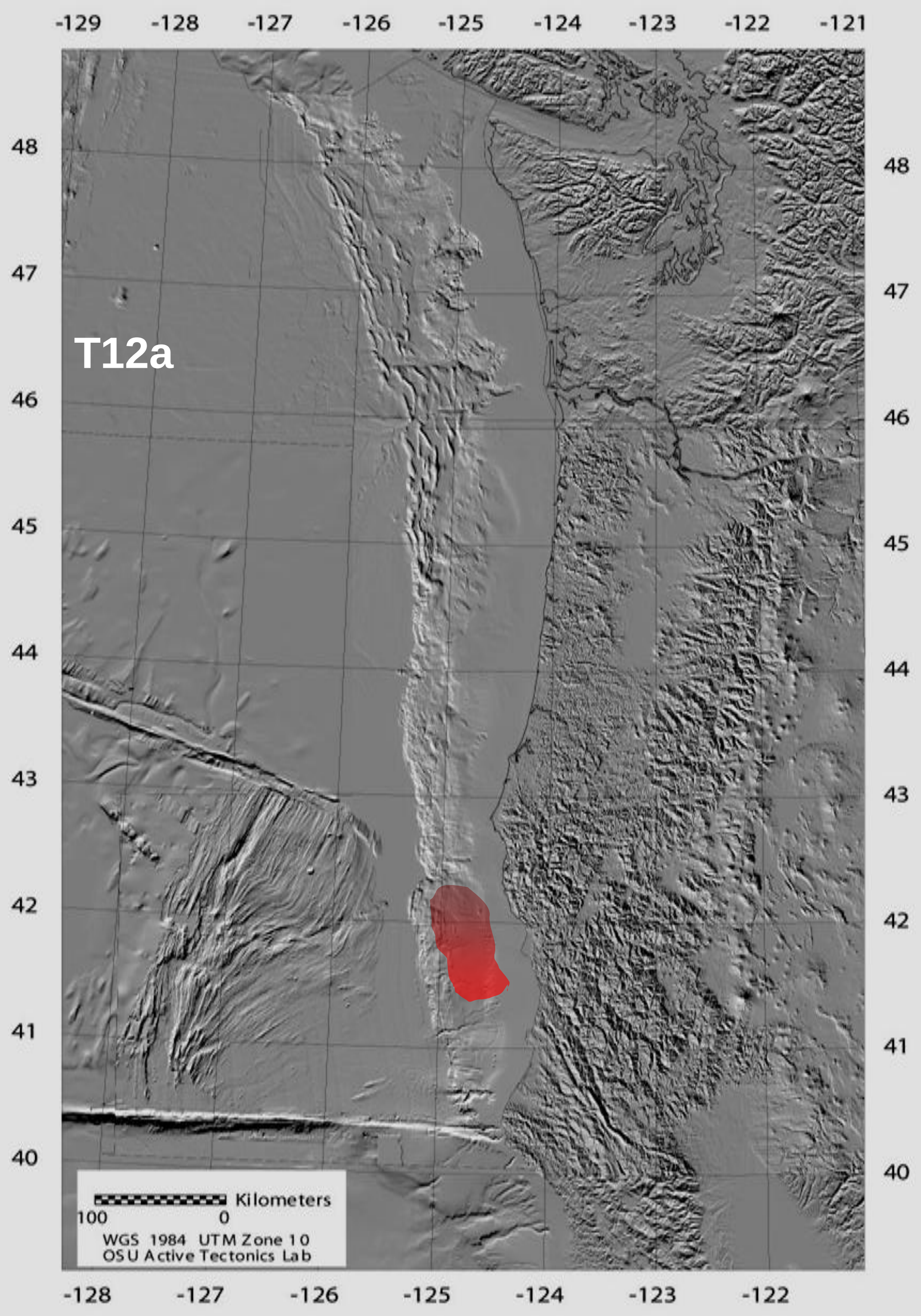
T15
-129 -128 -127 -126 -125 -124 -123 -122 -121
48
47
46
45
44
43
42
41
40
Kilometers
100 0
WGS 1984 UTM Zone 10
OSU Active Tectonics Lab
-128 -127 -126 -125 -124 -123 -122

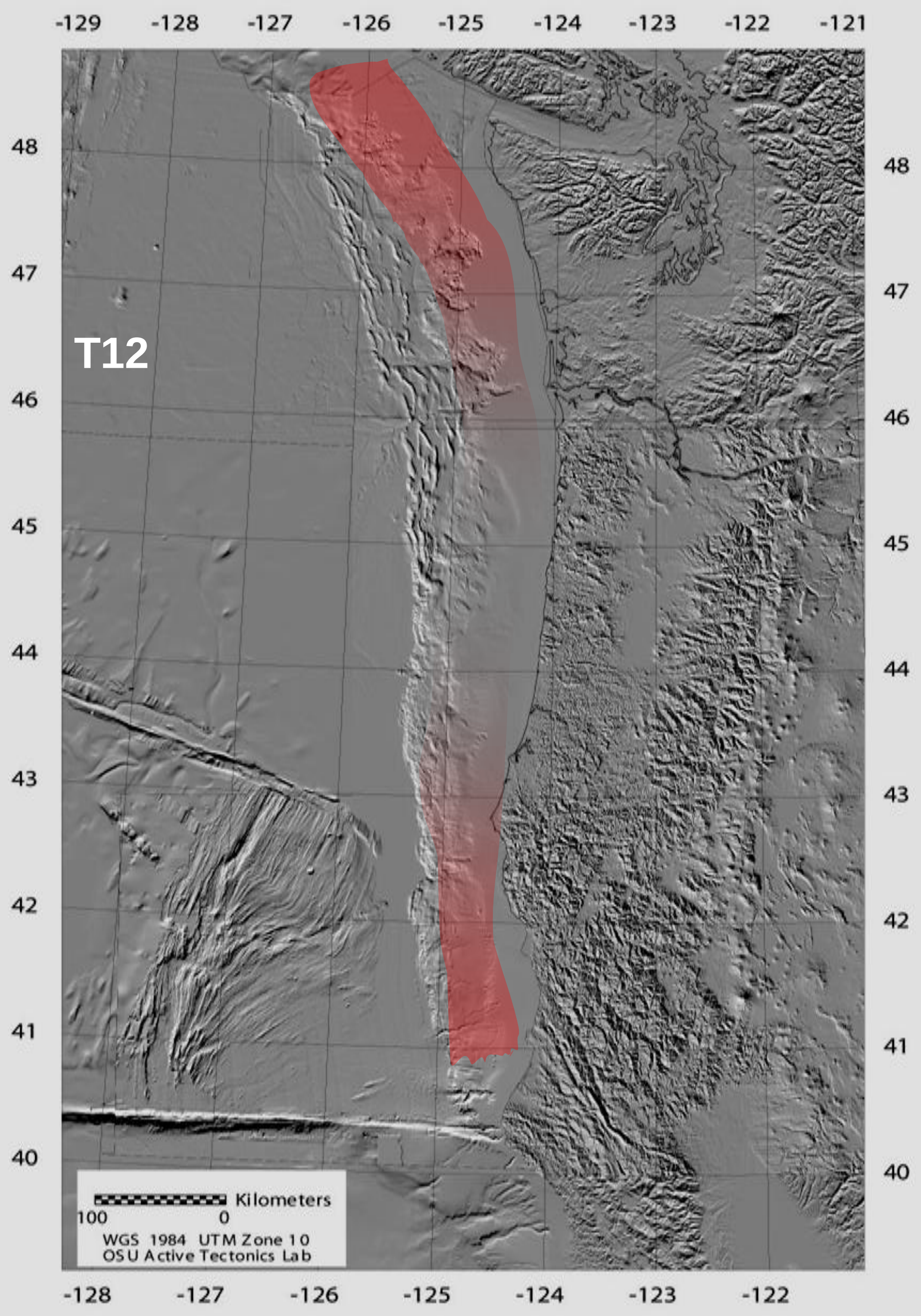

-129
-128
-127
-126
-125
-124
-123
-122
-121
48
47
46
45
44
43
42
41
40
T14a
Kilometers
100
0
WGS 1984 UTM Zone 10
OSU Active Tectonics Lab
-128
-127
-126
-125
-124
-123
-122

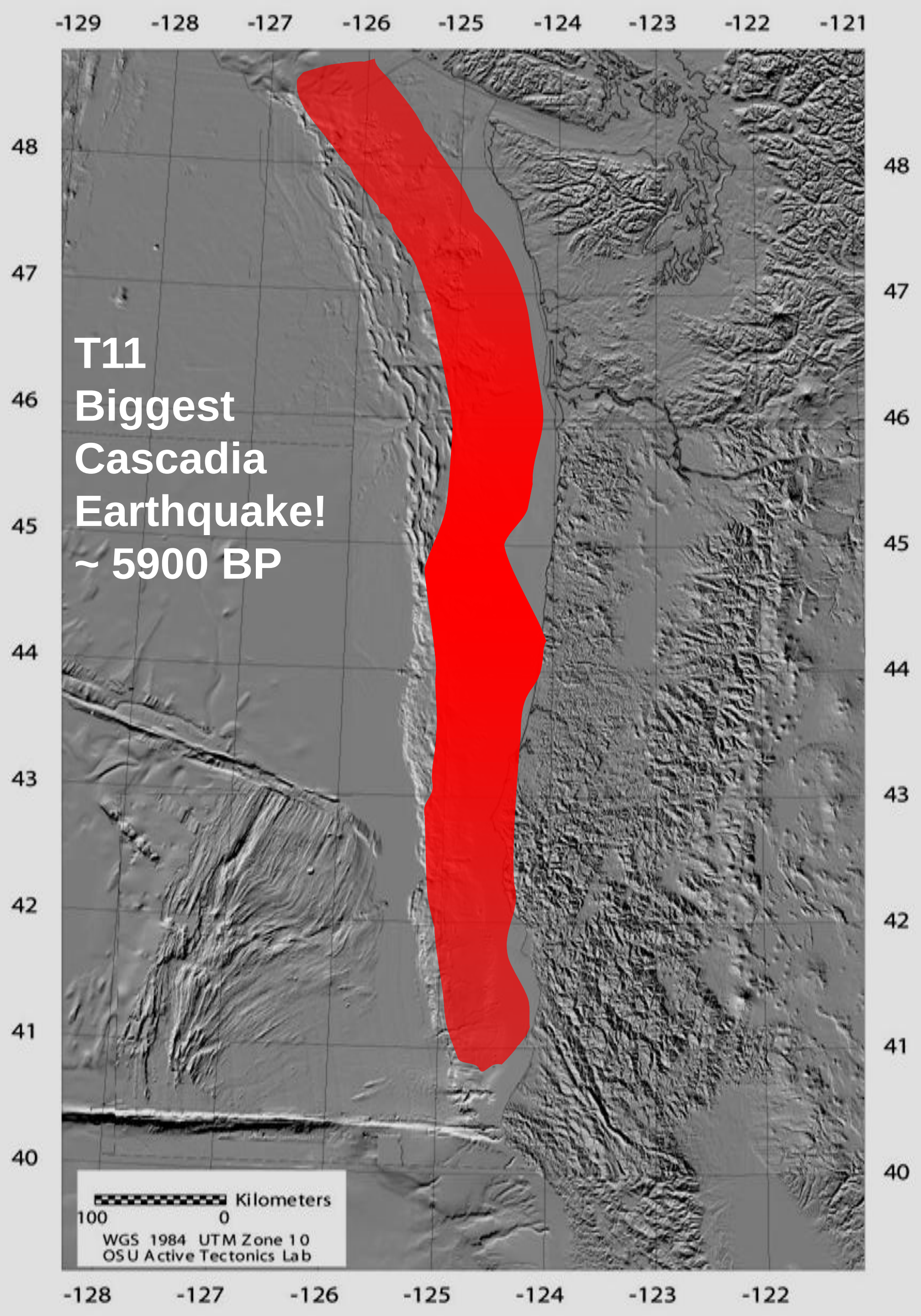


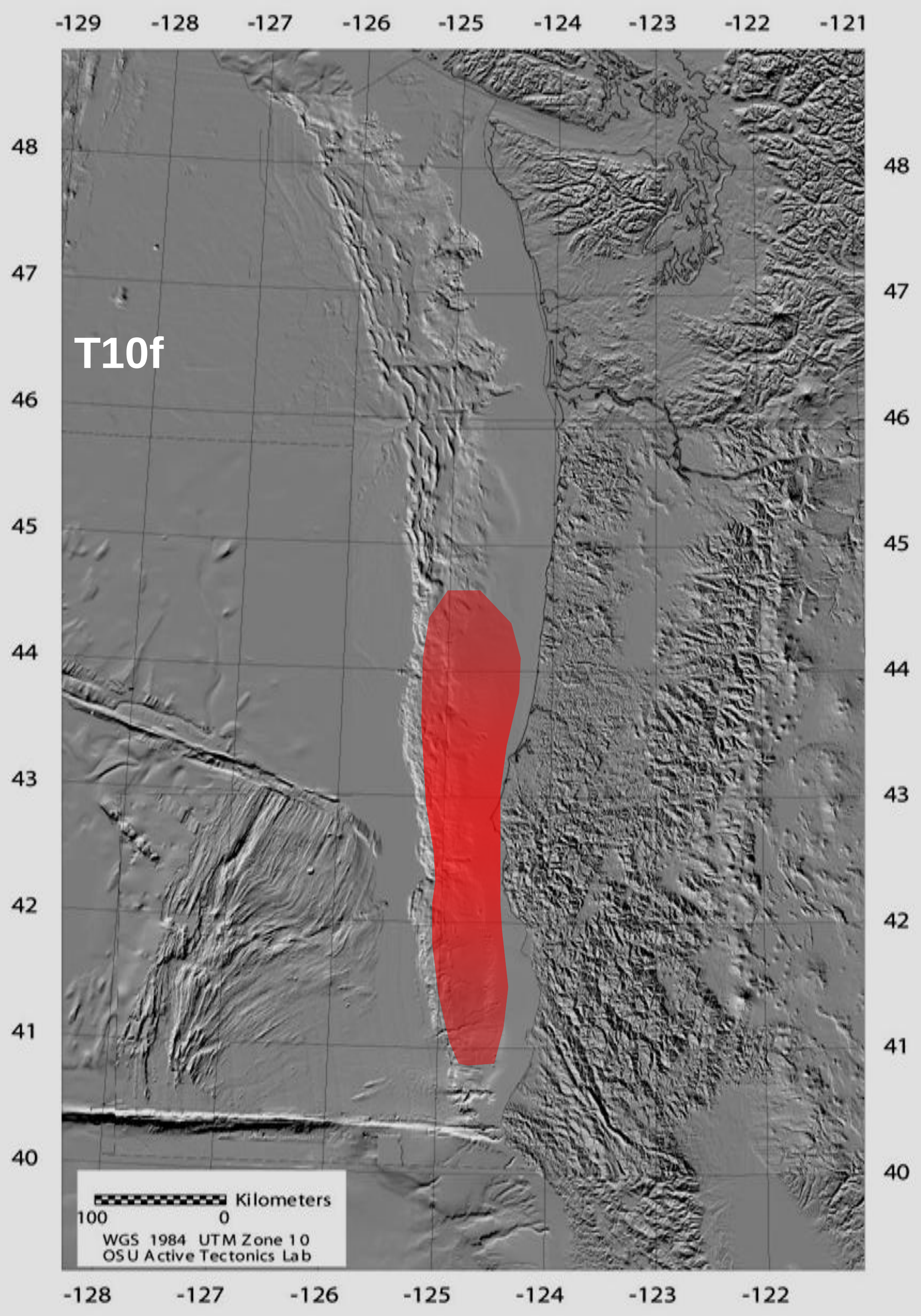
-129 -128 -127 -126 -125 -124 -123 -122 -121
48
47
46
45
44
43
42
41
40
T14 Crater Lake (Mt. Mazama) Goes off!! ~7625 BP
Kilometers
100 0
WGS 1984 UTM Zone 10
OSU Active Tectonics Lab
-128 -127 -126 -125 -124 -123 -122


-129
-128
-127
-126
-125
-124
-123
-122
-121
48
47
46
45
44
43
42
41
40
T13
Kilometers
100
0
WGS 1984 UTM Zone 10
OSU Active Tectonics Lab

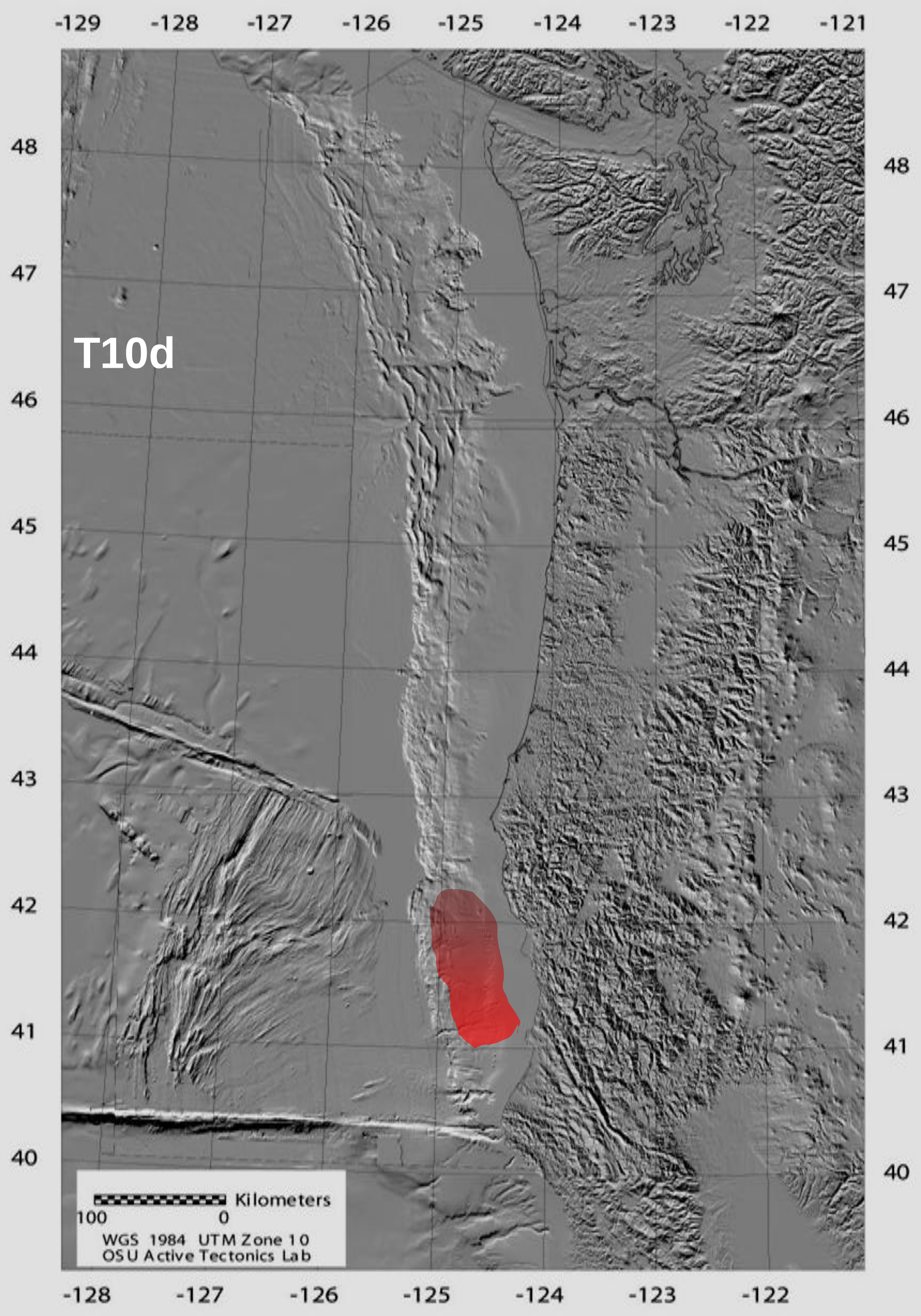

T12a
-129
-128
-127
-126
-125
-124
-123
-122
-121
48
47
46
45
44
43
42
41
40
Kilometers
100
0
WGS 1984 UTM Zone 10
OSU Active Tectonics Lab
-128
-127
-126
-125
-124
-123
-122


T12
Kilometers
100 0
WGS 1984 UTM Zone 10
OSU Active Tectonics Lab

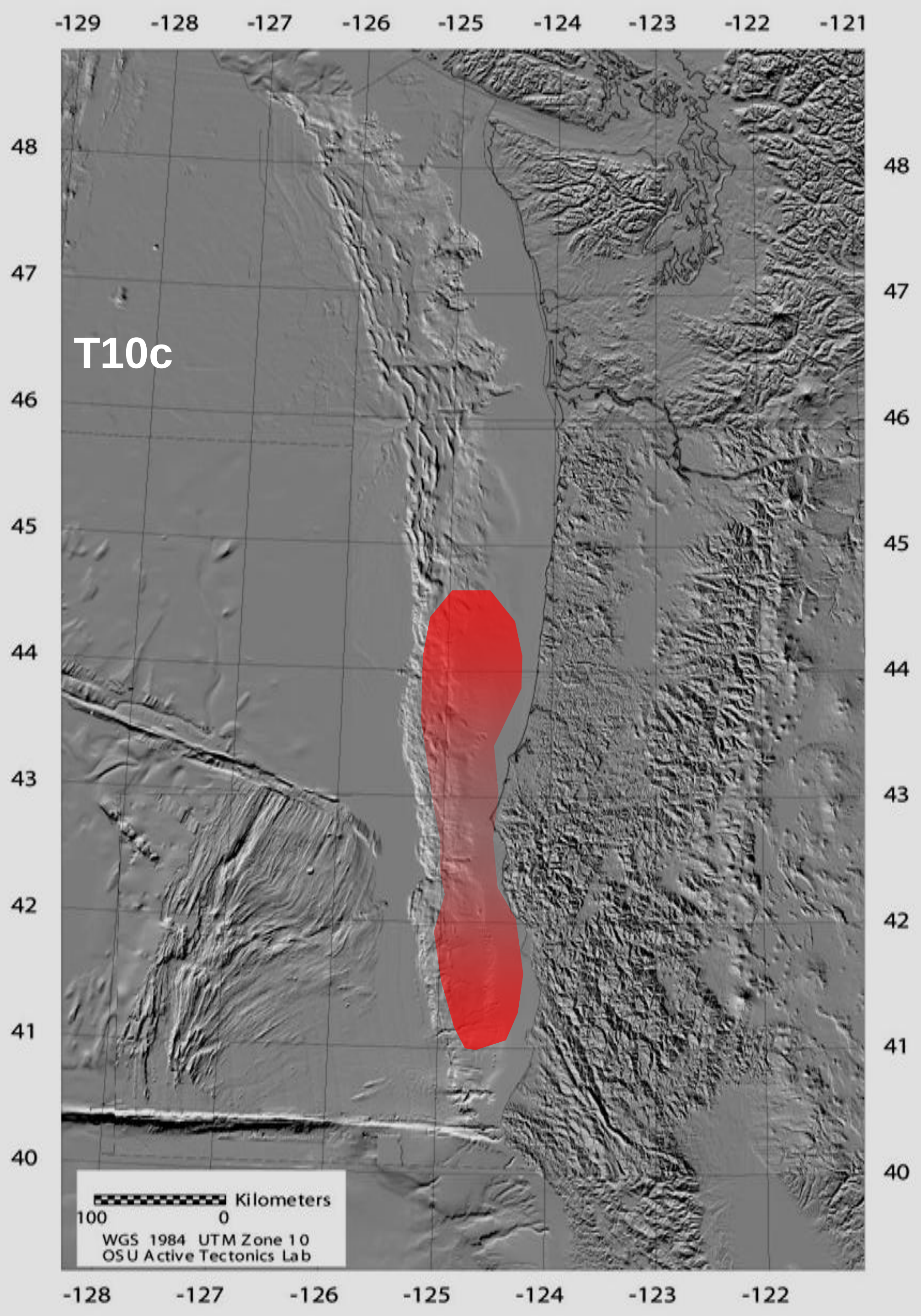

T11
Biggest
Cascadia
Earthquake!
~ 5900 BP
-129 -128 -127 -126 -125 -124 -123 -122 -121
48
47
46
45
44
43
42
41
40
-128 -127 -126 -125 -124 -123 -122
Kilometers
100 0
WGS 1984 UTM Zone 10
OSU Active Tectonics Lab



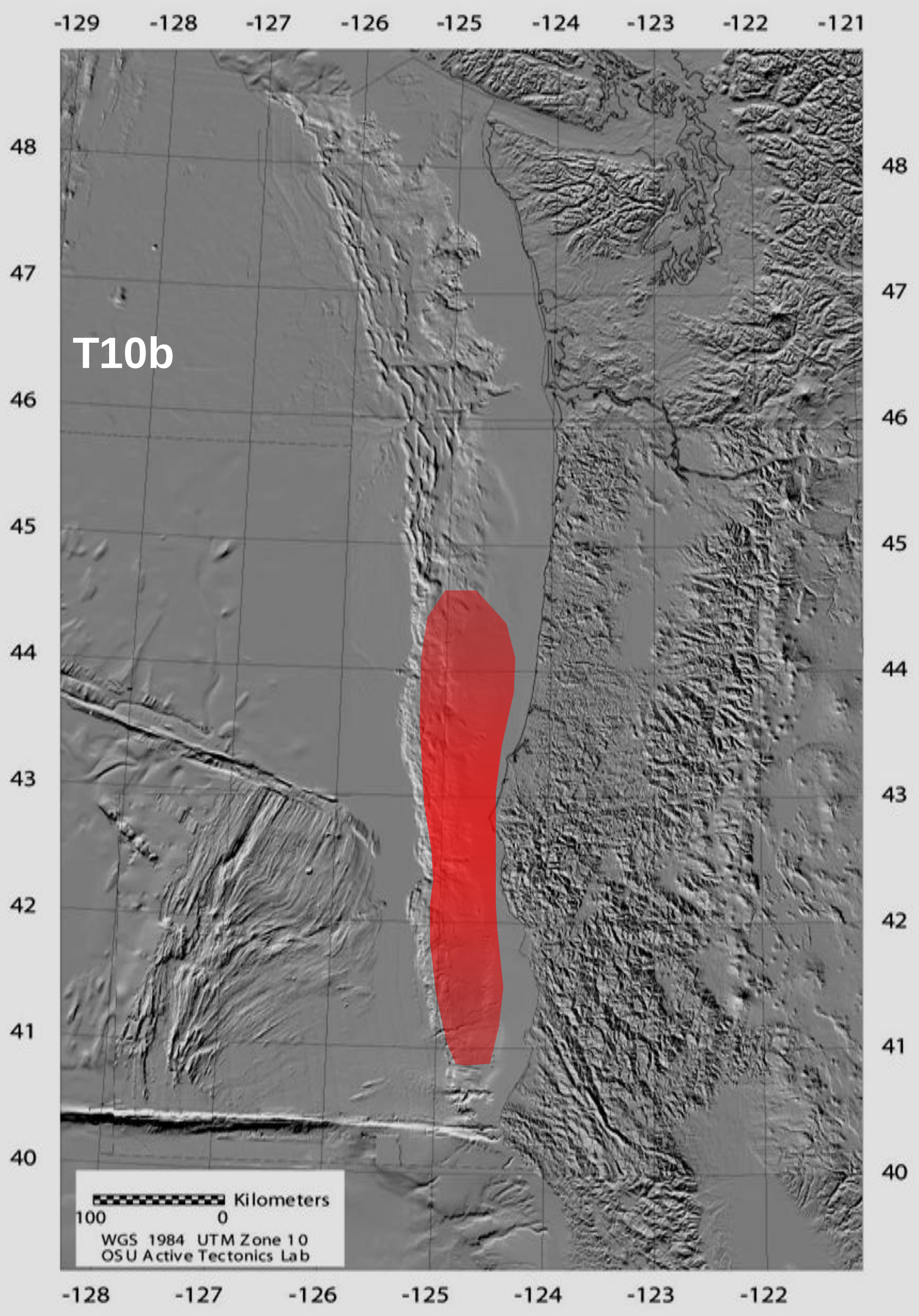
-129 -128 -127 -126 -125 -124 -123 -122 -121
48 47 46 45 44 43 42 41 40
T10f
Kilometers
100 0
WGS 1984 UTM Zone 10
OSU Active Tectonics Lab
-128 -127 -126 -125 -124 -123 -122

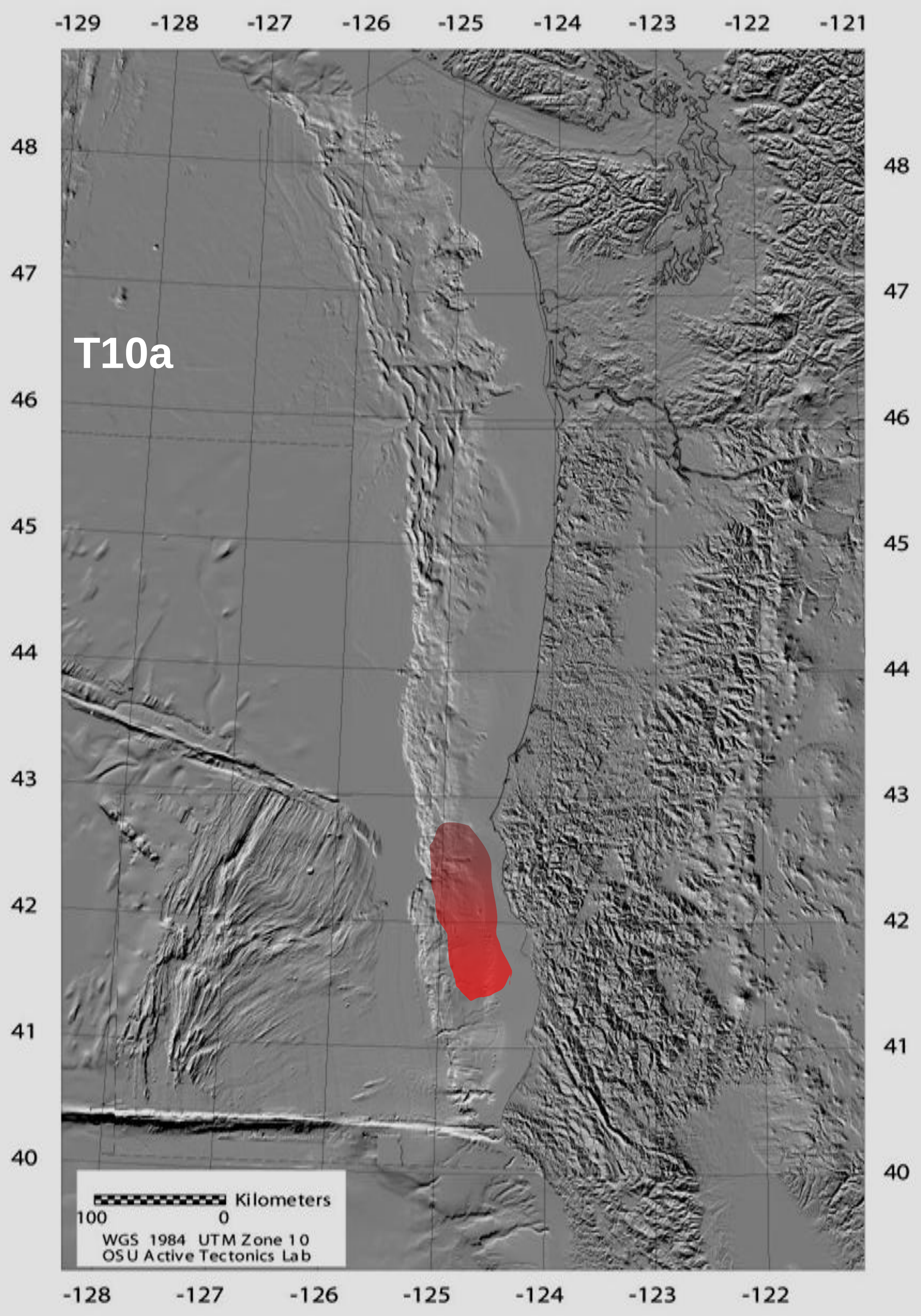


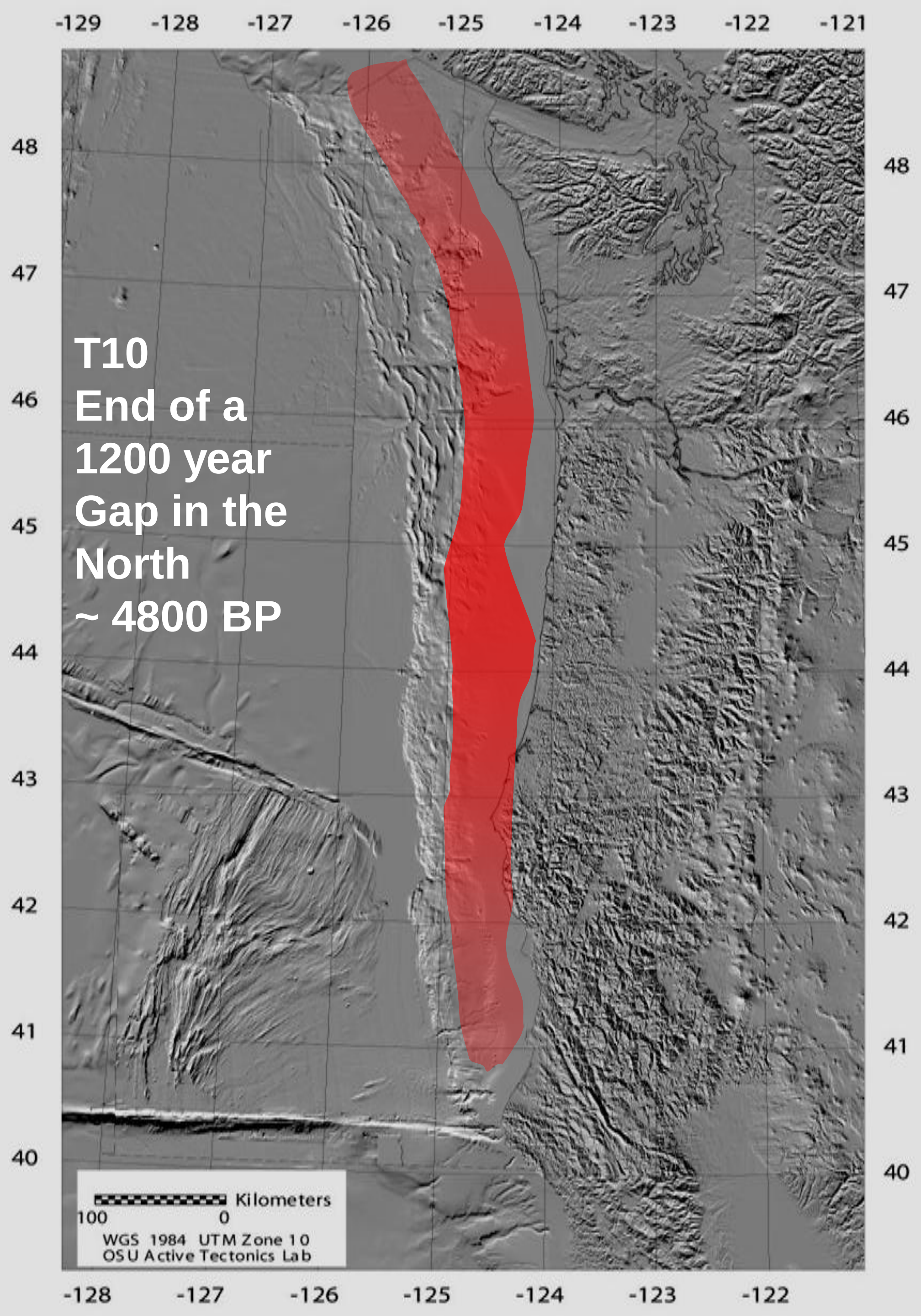
T10d
-129
-128
-127
-126
-125
-124
-123
-122
-121
48
47
46
45
44
43
42
41
40
Kilometers
100
0
WGS 1984 UTM Zone 10
OSU Active Tectonics Lab

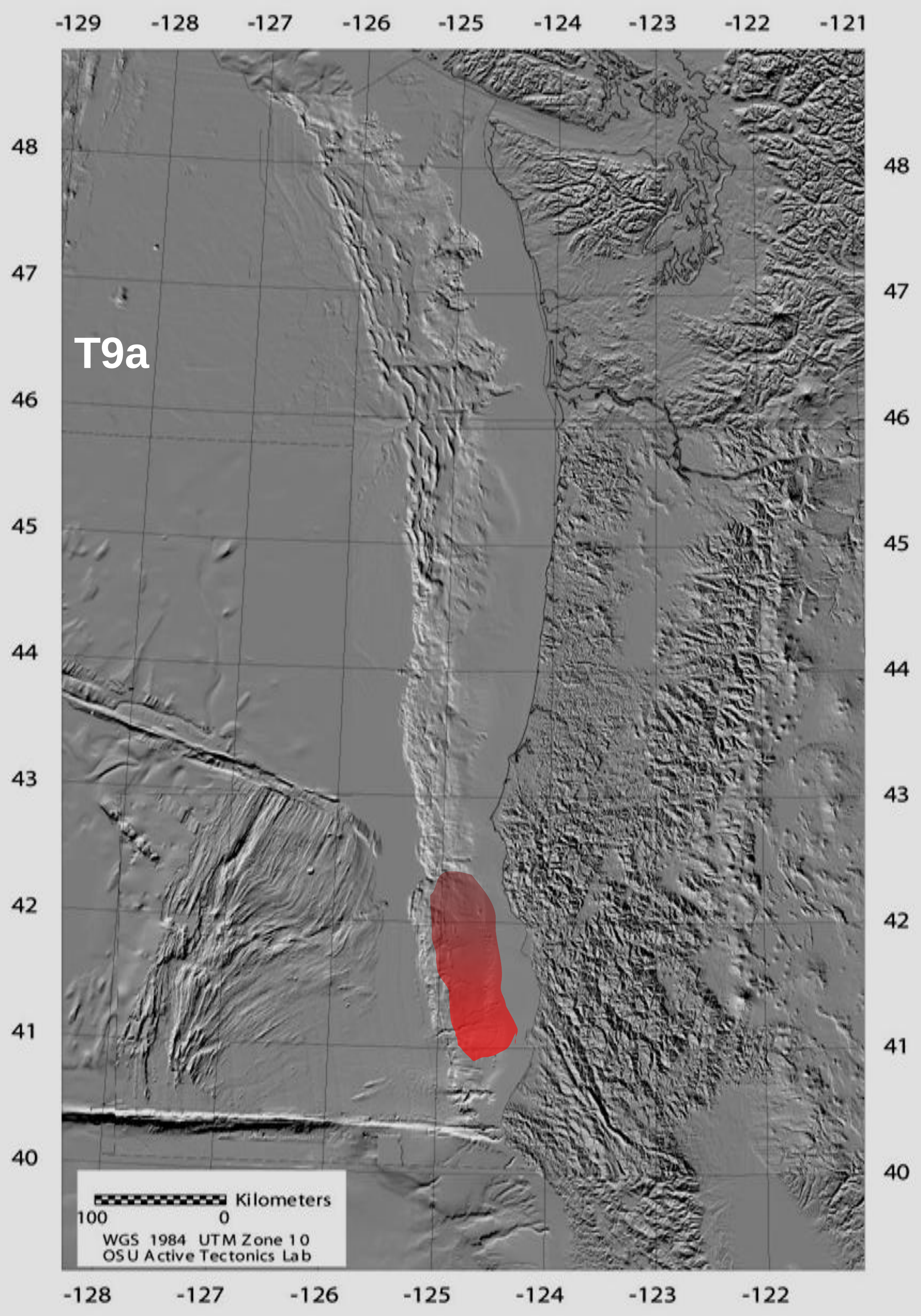


-129
-128
-127
-126
-125
-124
-123
-122
-121
48
47
46
45
44
43
42
41
40
T10c
Kilometers
100
0
WGS 1984 UTM Zone 10
OSU Active Tectonics Lab
-128
-127
-126
-125
-124
-123
-122

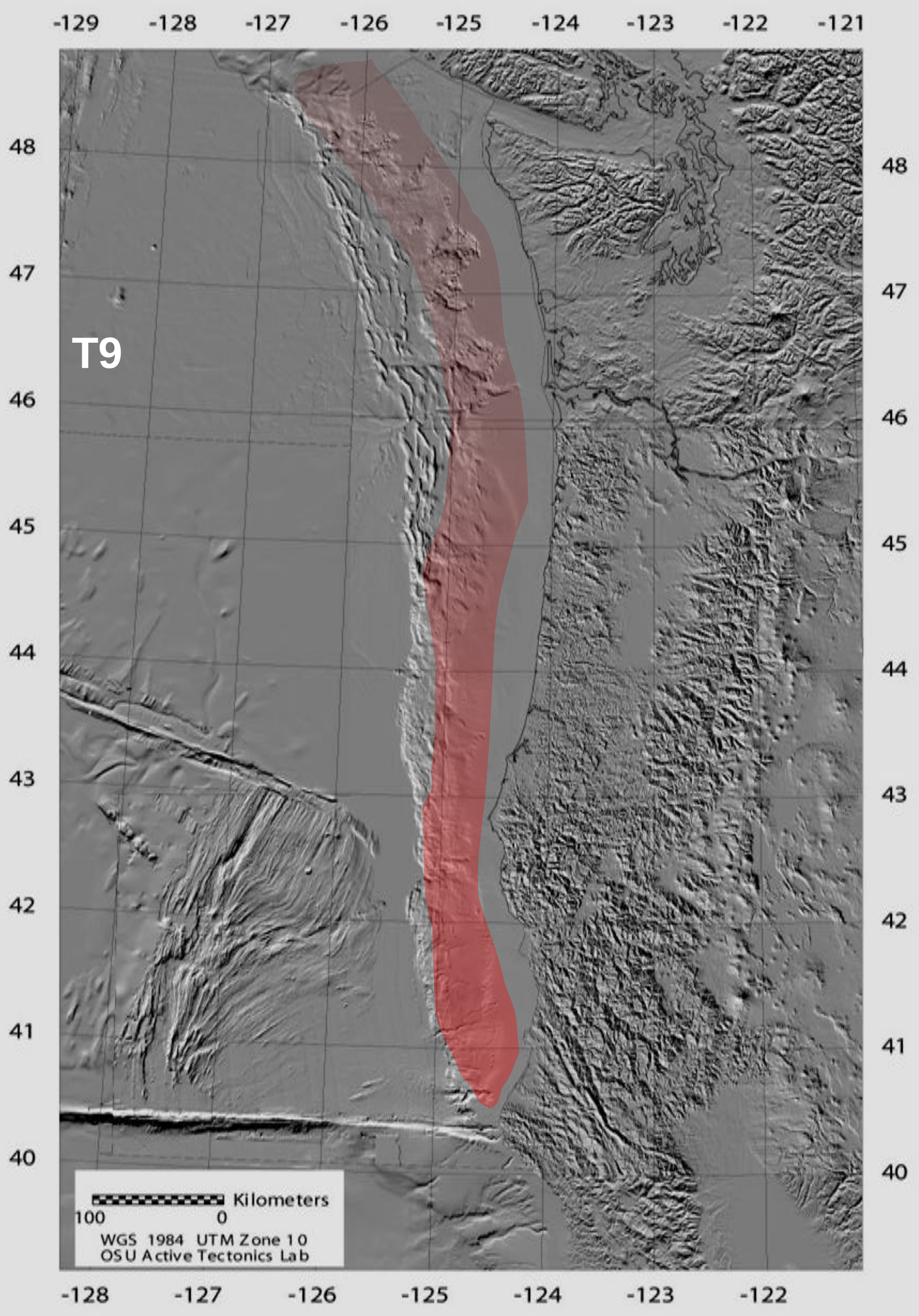

-129 -128 -127 -126 -125 -124 -123 -122 -121
48
47
46
45
44
43
42
41
40
T10b
Kilometers
100 0
WGS 1984 UTM Zone 10
OSU Active Tectonics Lab
-128 -127 -126 -125 -124 -123 -122

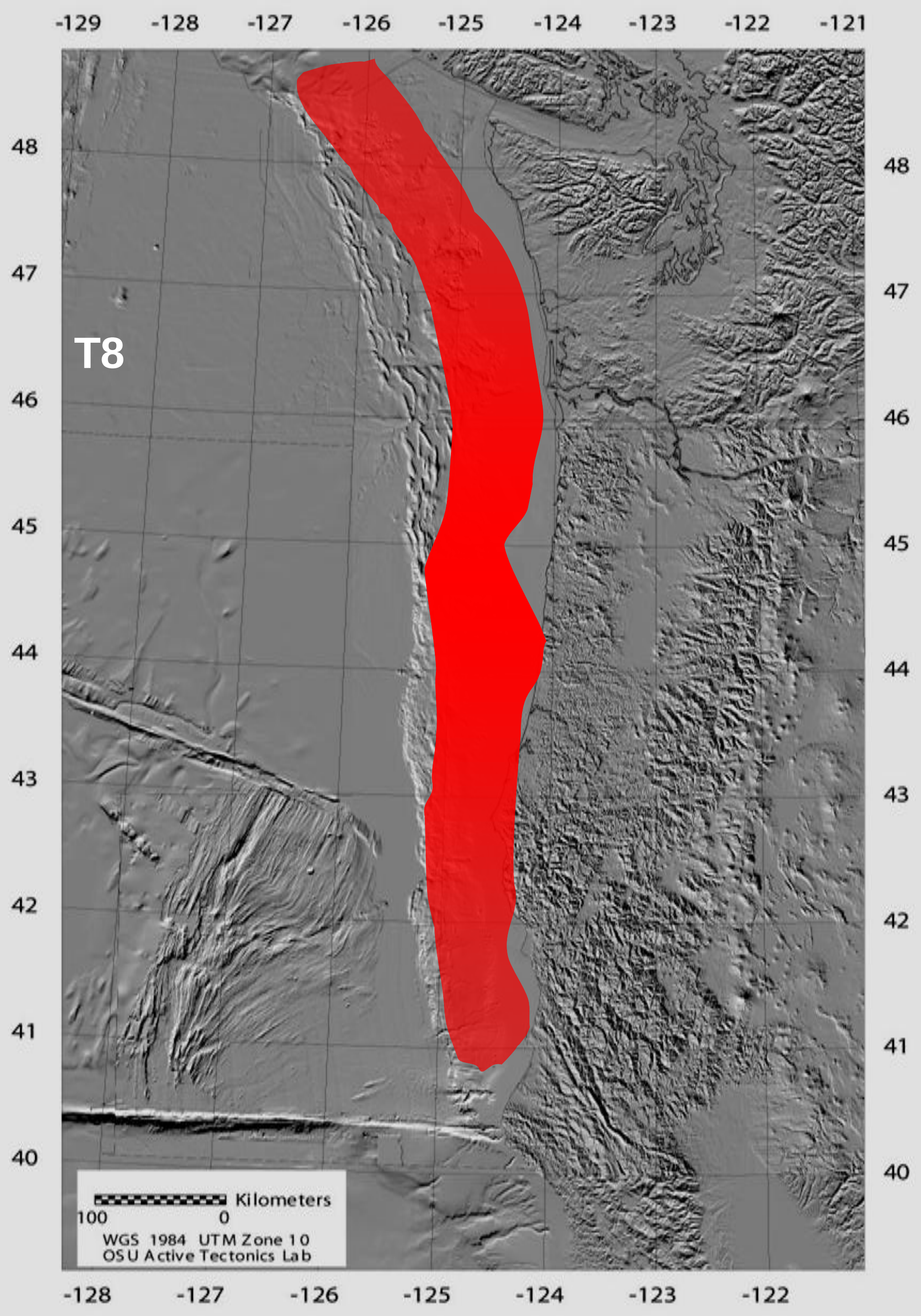

-129
-128
-127
-126
-125
-124
-123
-122
-121
48
47
46
45
44
43
42
41
40
T10a
Kilometers
100
0
WGS 1984 UTM Zone 10
OSU Active Tectonics Lab
-128
-127
-126
-125
-124
-123
-122

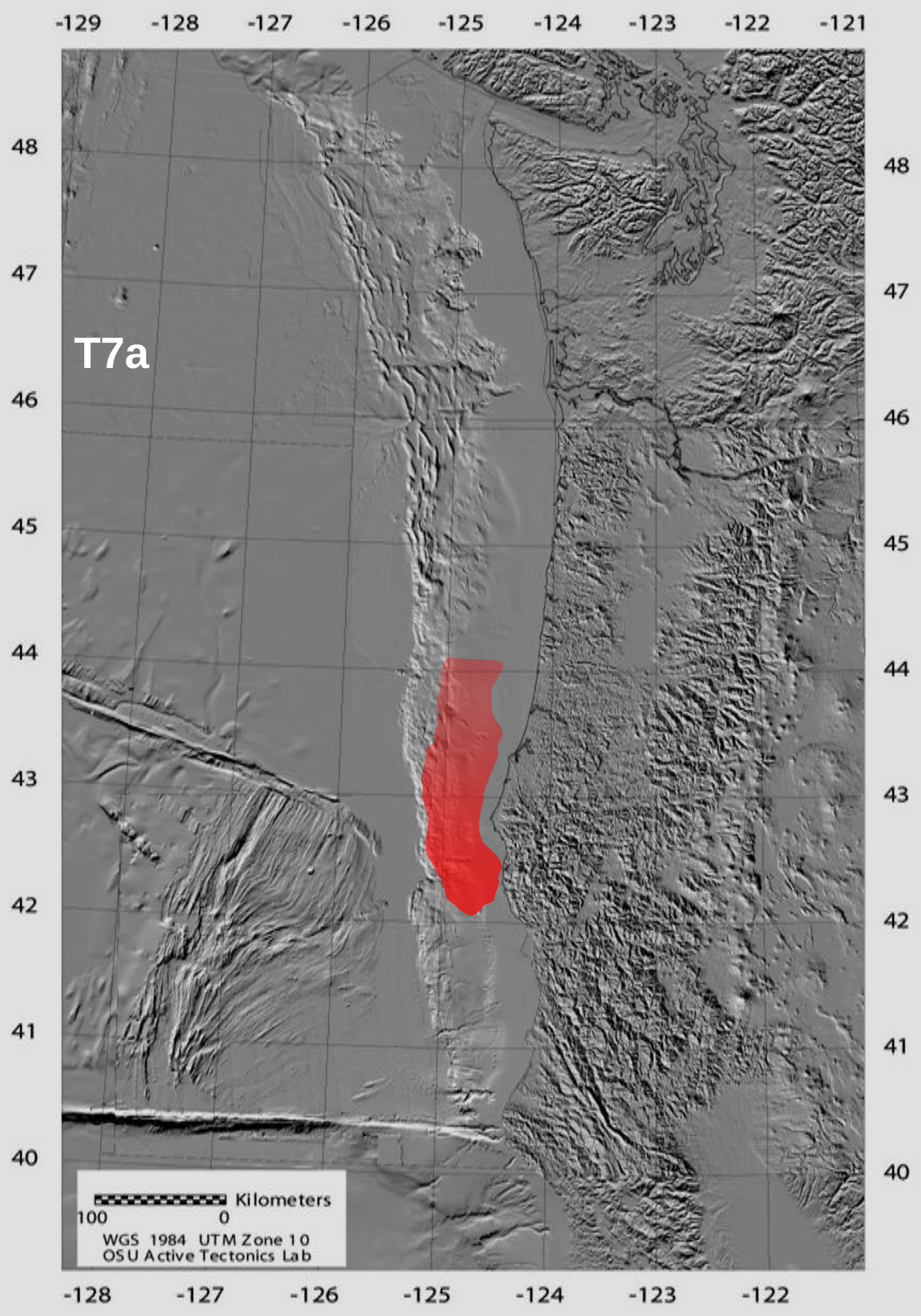

-129 -128 -127 -126 -125 -124 -123 -122 -121
48
47
46
45
44
43
42
41
40
T10
End of a
1200 year
Gap in the
North
~ 4800 BP
Kilometers
100 0
WGS 1984 UTM Zone 10
OSU Active Tectonics Lab
-128 -127 -126 -125 -124 -123 -122



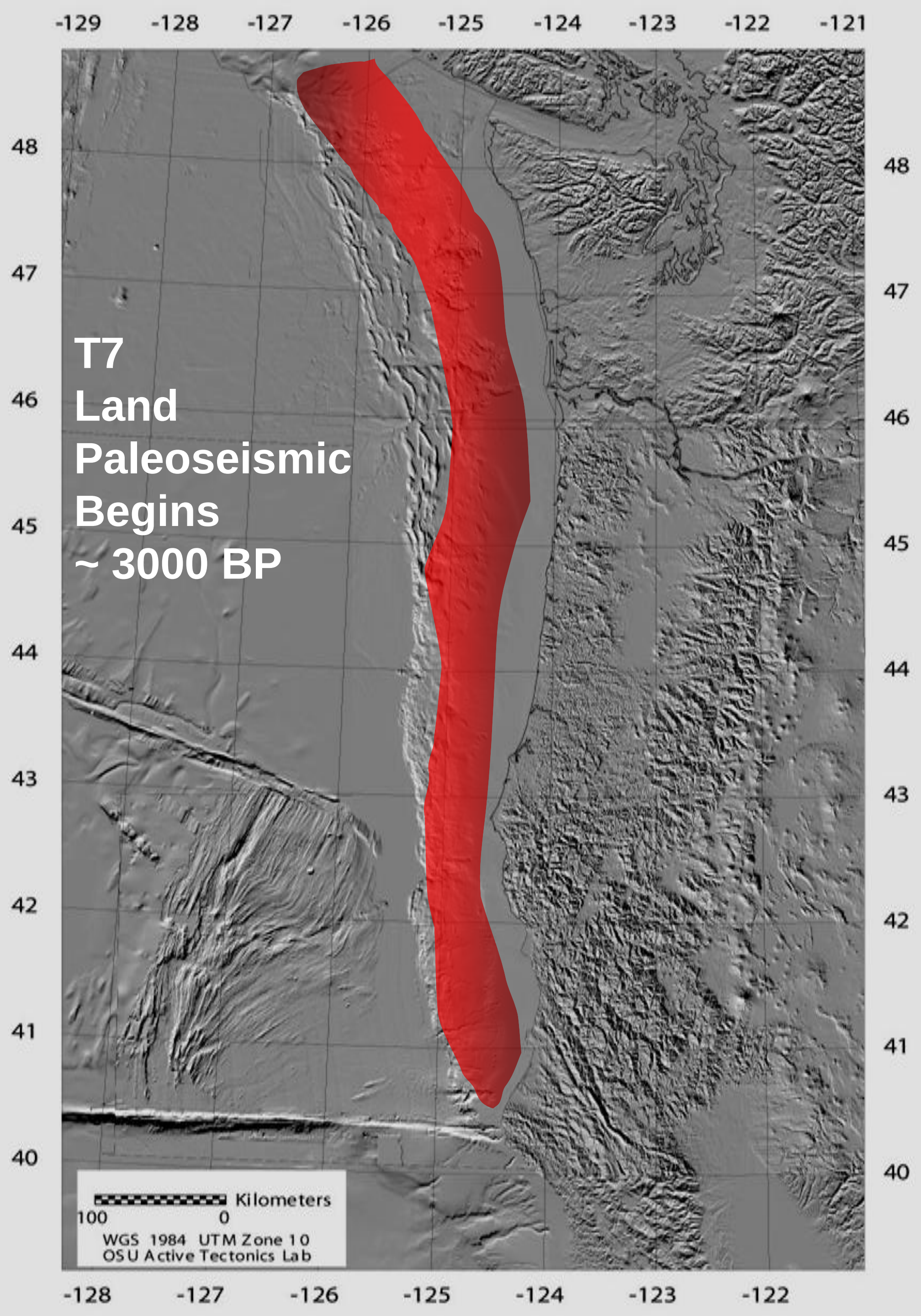
-129 -128 -127 -126 -125 -124 -123 -122 -121
48 47 46 45 44 43 42 41 40
T9a
Kilometers
100 0
WGS 1984 UTM Zone 10
OSU Active Tectonics Lab
-128 -127 -126 -125 -124 -123 -122

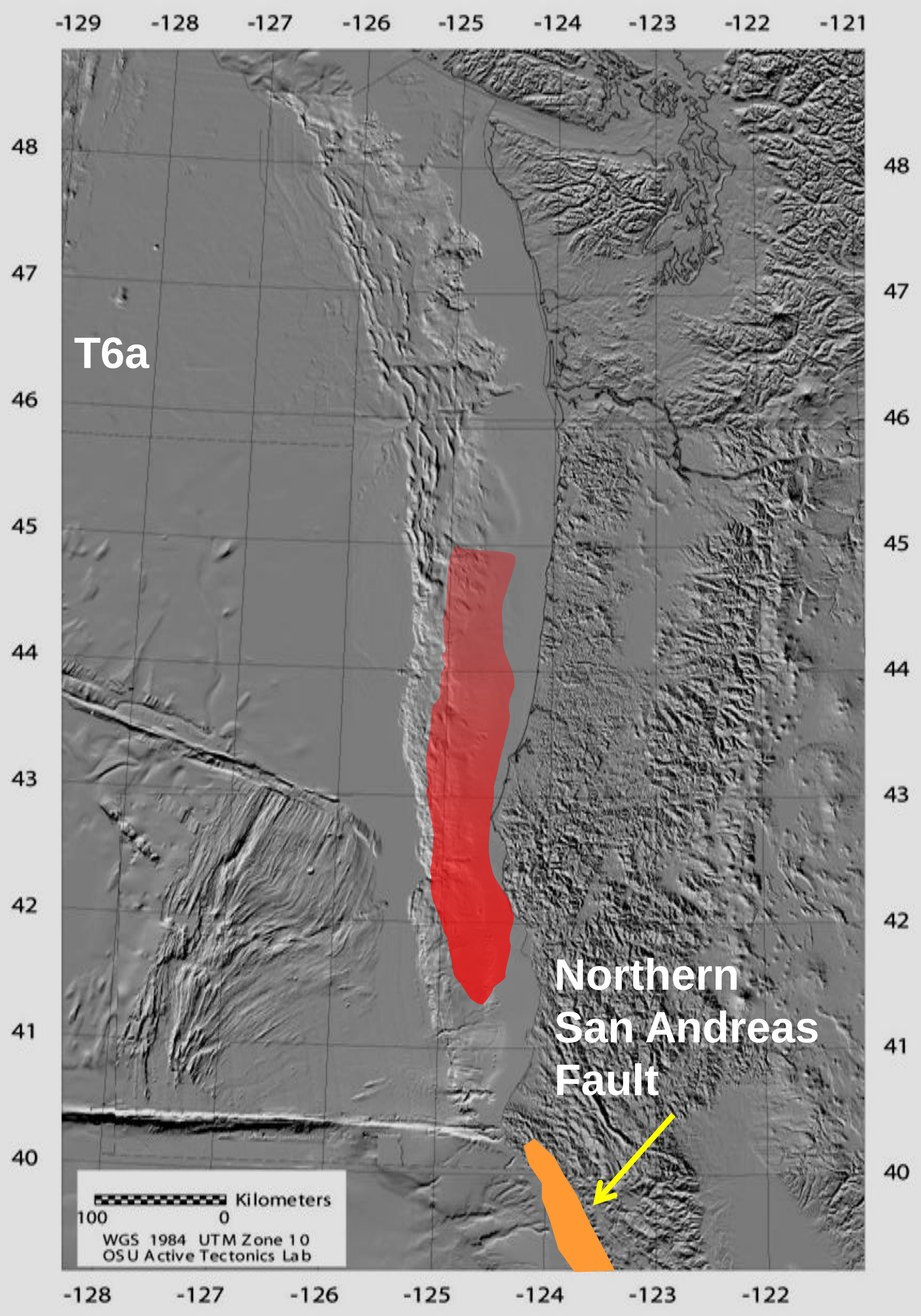

-129
-128
-127
-126
-125
-124
-123
-122
-121
48
47
46
45
44
43
42
41
40
T9
Kilometers
100
0
WGS 1984 UTM Zone 10
OSU Active Tectonics Lab

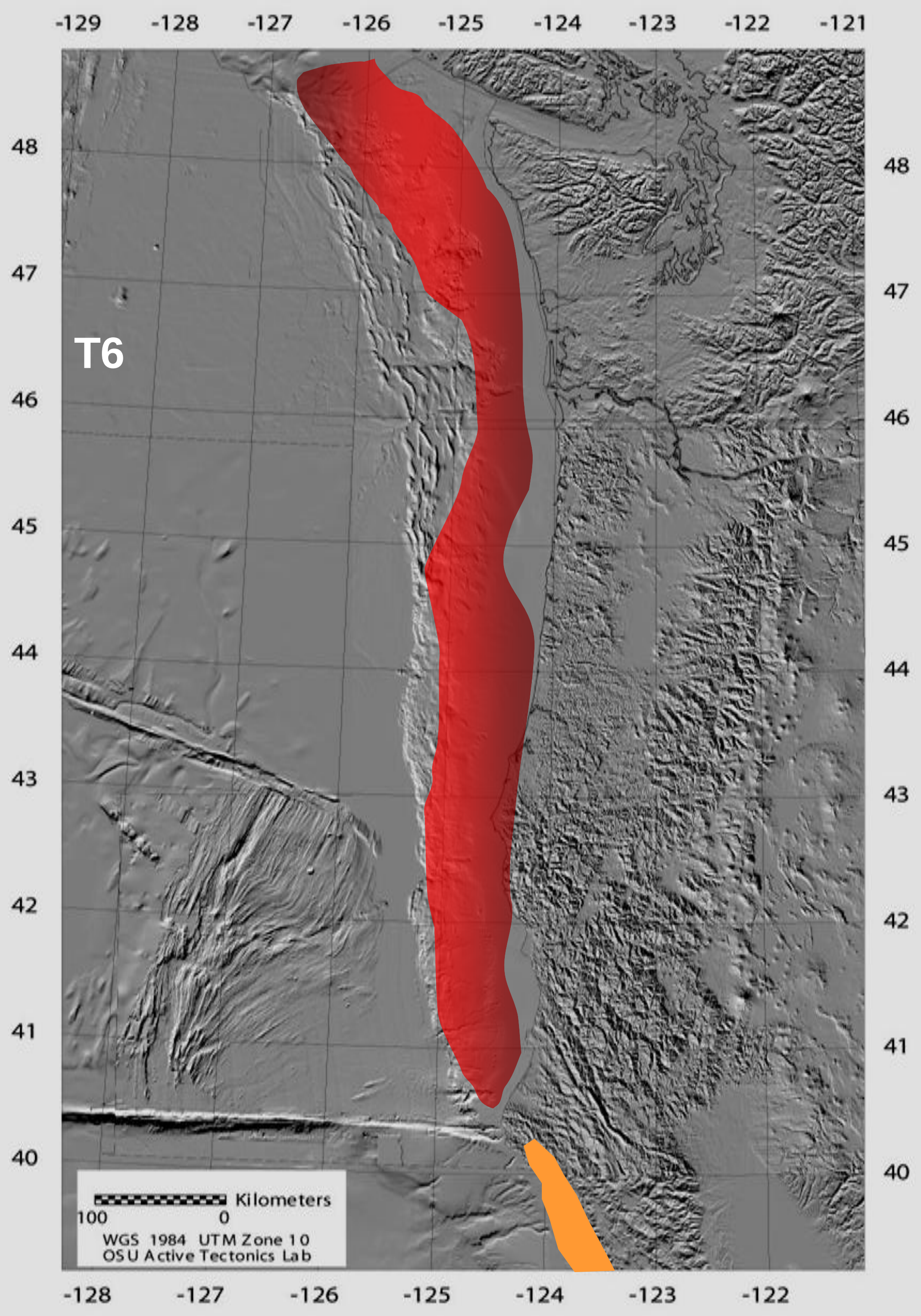

-129 -128 -127 -126 -125 -124 -123 -122 -121
48
47
46
45
44
43
42
41
40
T8
Kilometers
100 0
WGS 1984 UTM Zone 10
OSU Active Tectonics Lab
-128 -127 -126 -125 -124 -123 -122

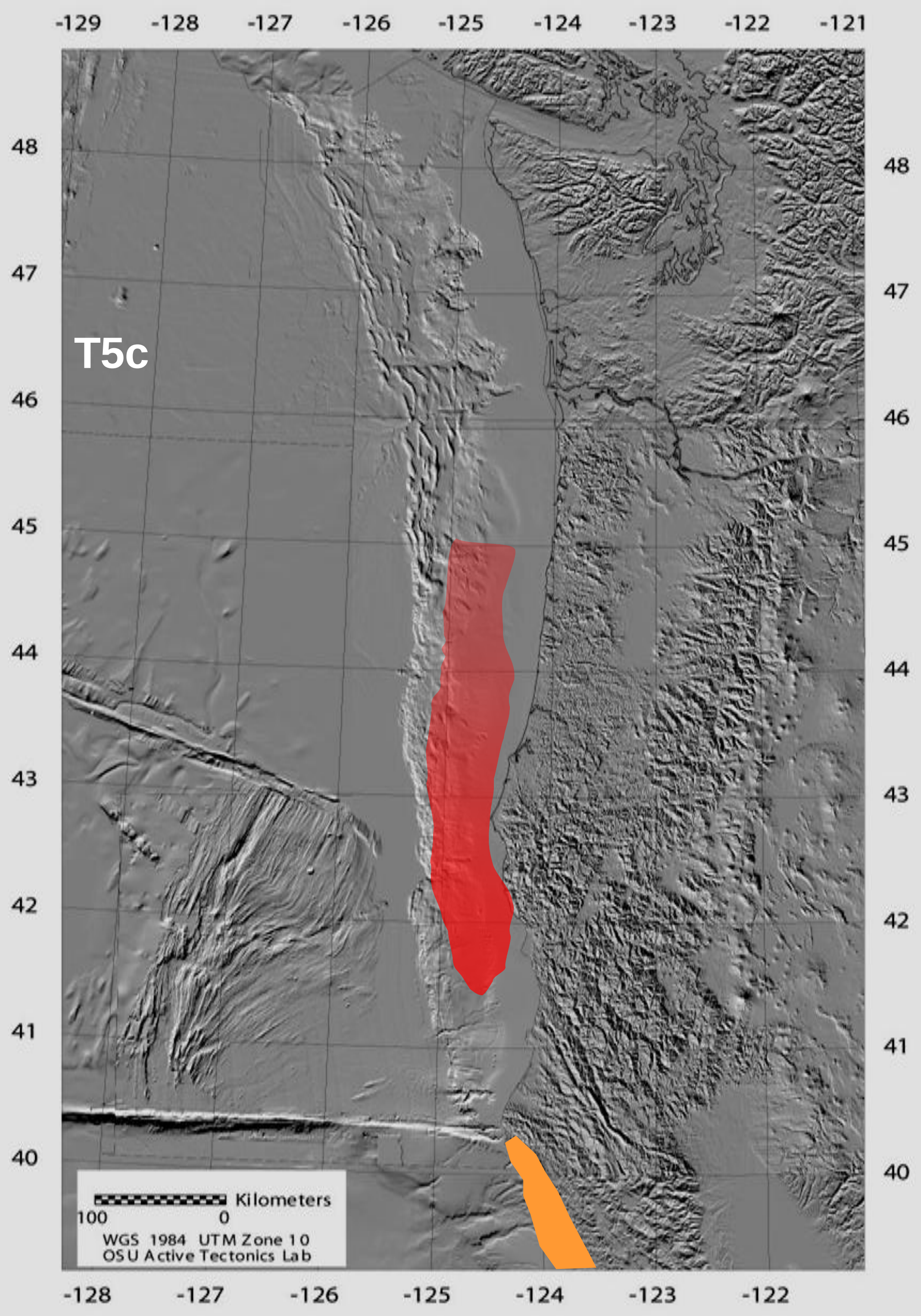


T7a
-129
-128
-127
-126
-125
-124
-123
-122
-121
48
47
46
45
44
43
42
41
40
Kilometers
100
0
WGS 1984 UTM Zone 10
OSU Active Tectonics Lab

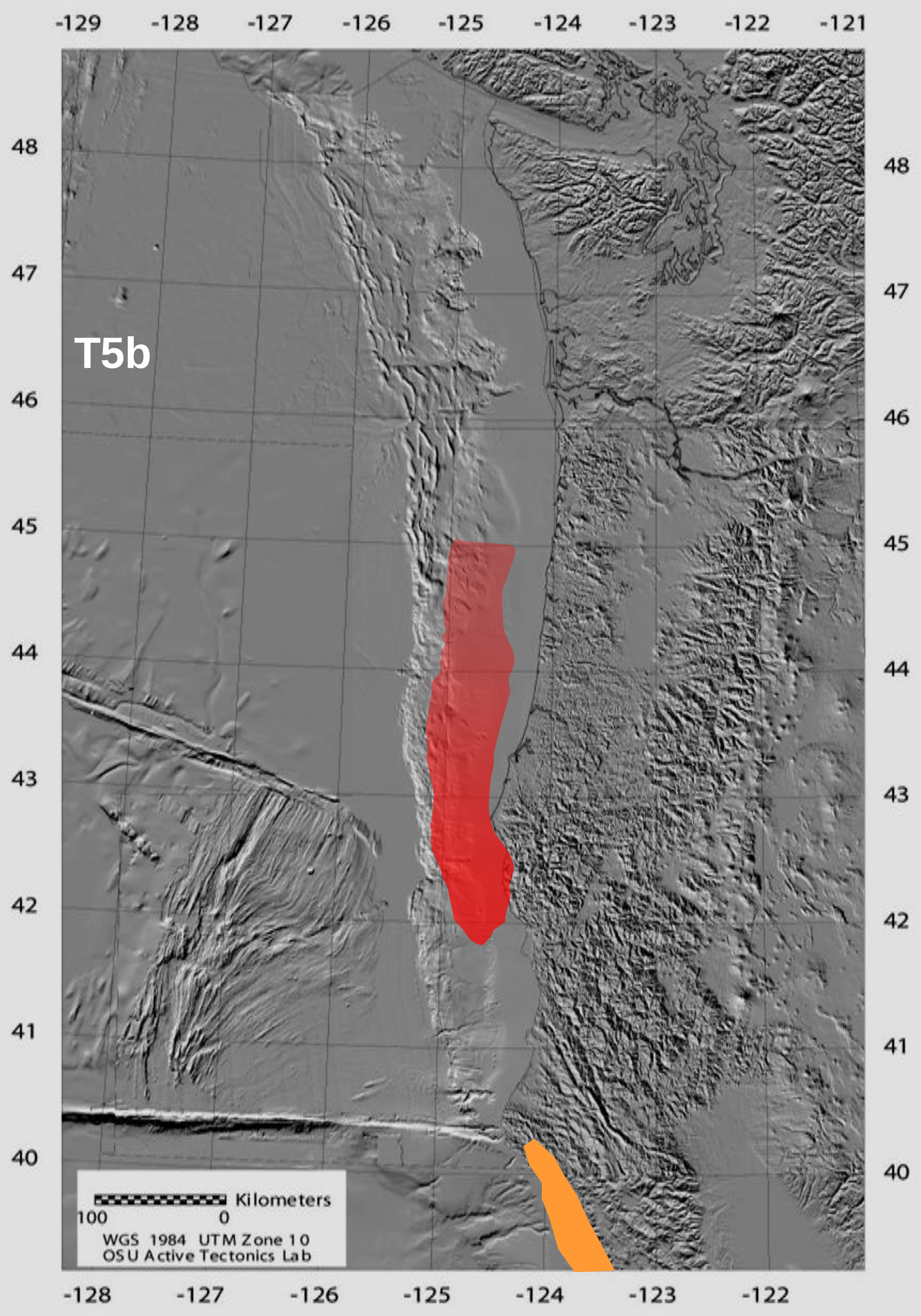

-129
-128
-127
-126
-125
-124
-123
-122
-121
48
47
46
45
44
43
42
41
40
T7
Land
Paleoseismic
Begins
~ 3000 BP
Kilometers
100
0
WGS 1984 UTM Zone 10
OSU Active Tectonics Lab
-128
-127
-126
-125
-124
-123
-122


-129
-128
-127
-126
-125
-124
-123
-122
-121
48
47
46
45
44
43
42
41
40
T6a
Northern
San Andreas
Fault
Kilometers
100
0
WGS 1984 UTM Zone 10
OSU Active Tectonics Lab
-128
-127
-126
-125
-124
-123
-122

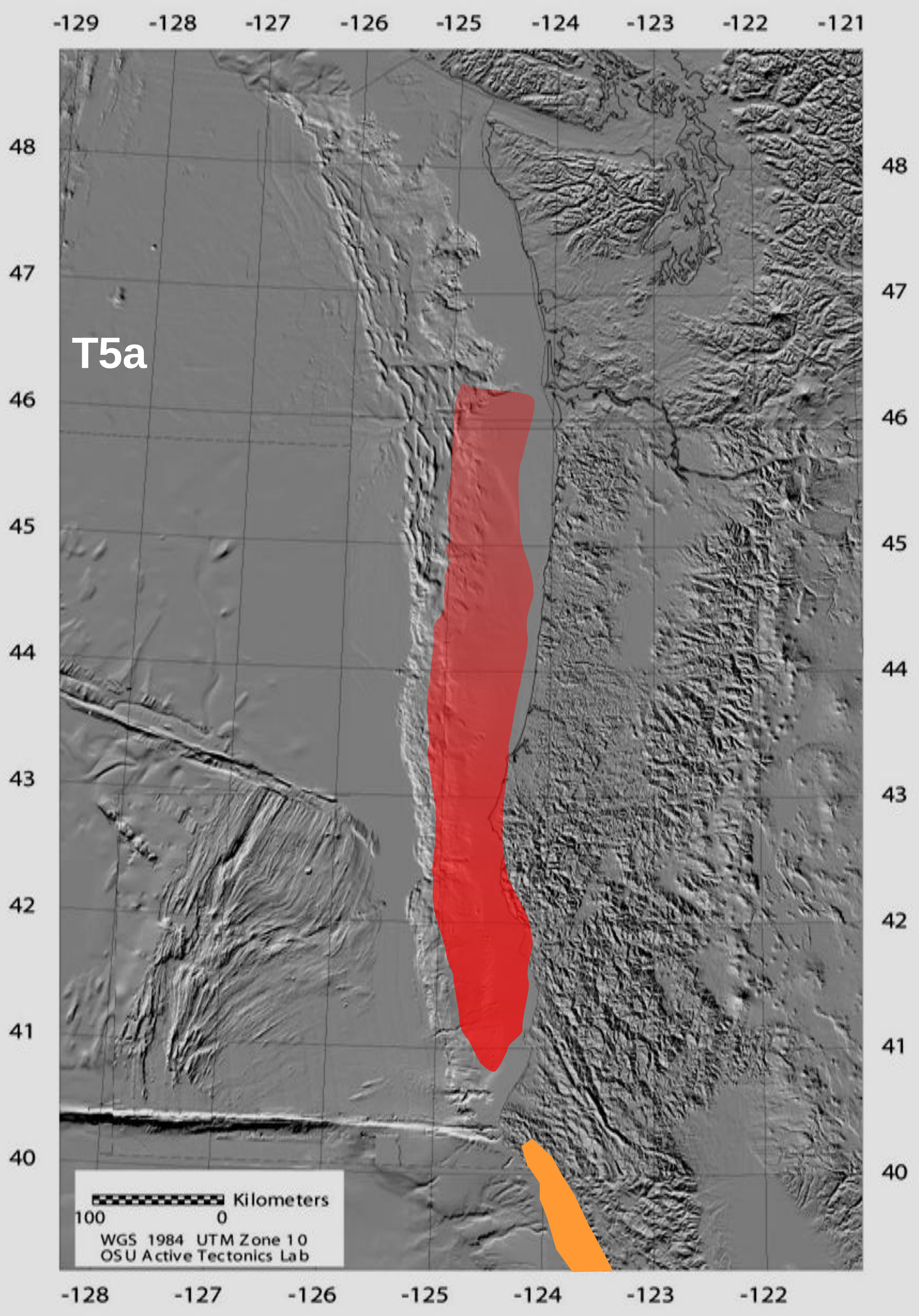

-129
-128
-127
-126
-125
-124
-123
-122
-121
48
47
46
45
44
43
42
41
40
T6
Kilometers
100
0
WGS 1984 UTM Zone 10
OSU Active Tectonics Lab
-128
-127
-126
-125
-124
-123
-122



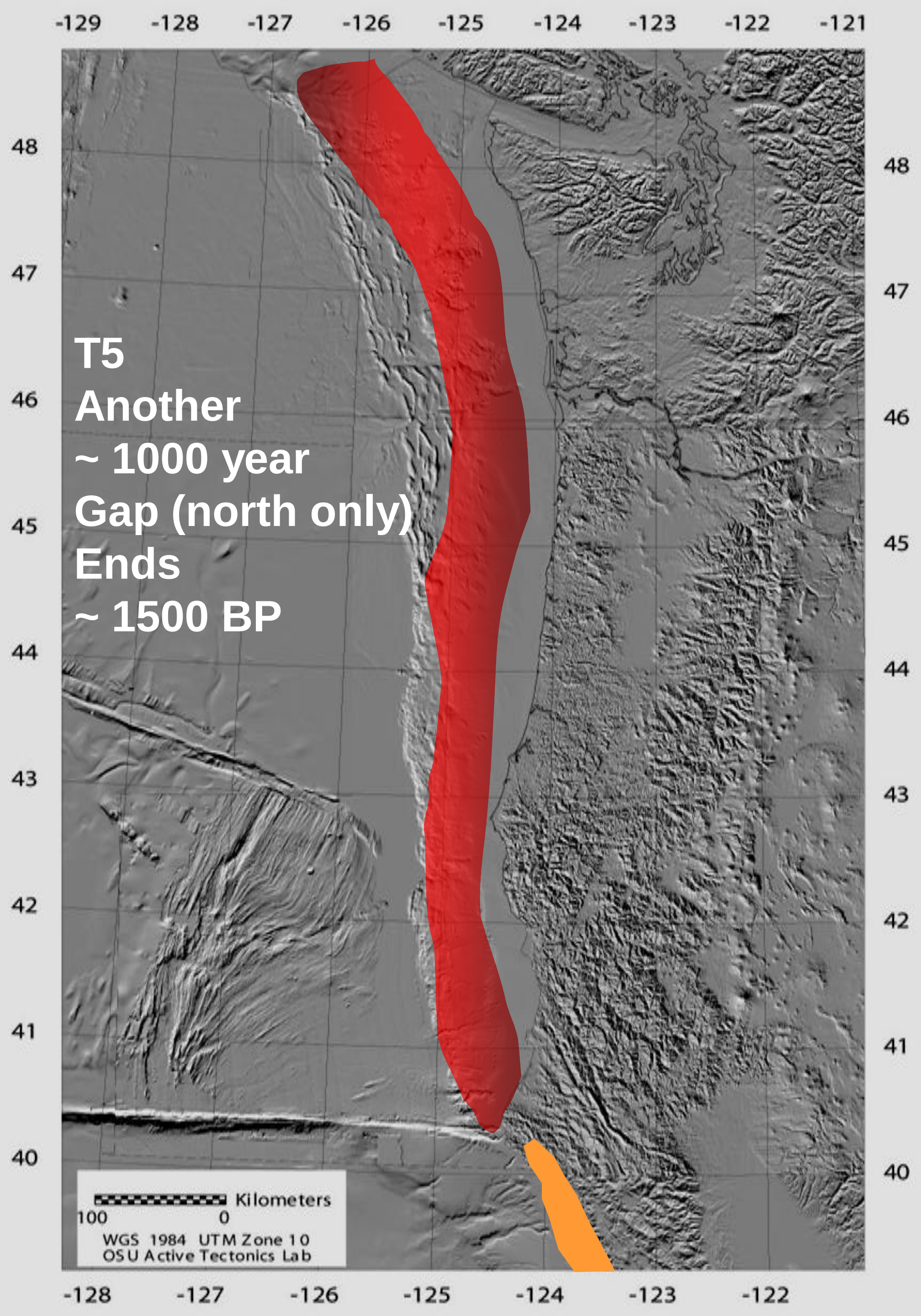
-129
-128
-127
-126
-125
-124
-123
-122
-121
48
47
46
45
44
43
42
41
40
T5c
Kilometers
100
0
WGS 1984 UTM Zone 10
OSU Active Tectonics Lab
-128
-127
-126
-125
-124
-123
-122



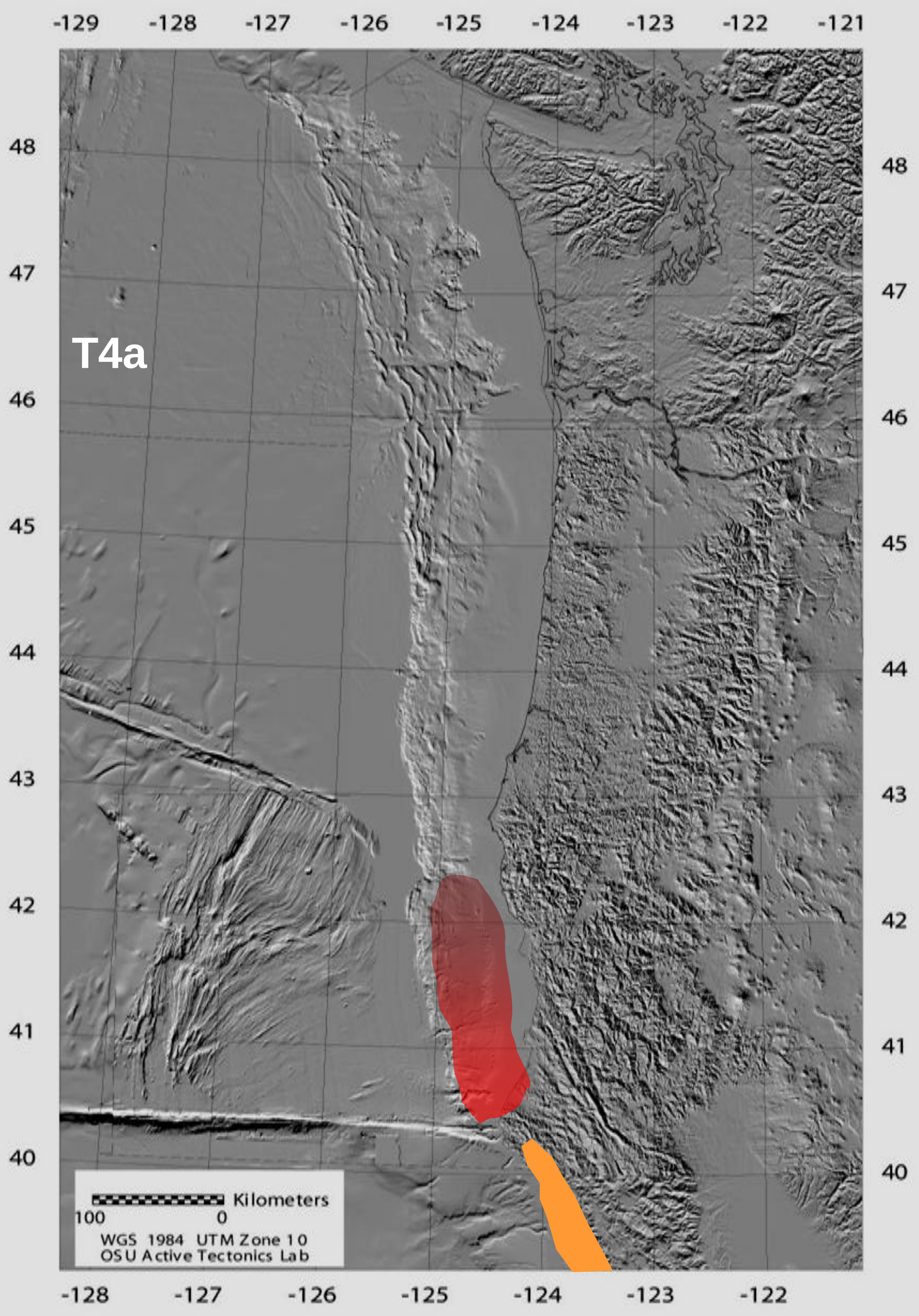
NTHMP Workshop, 2012

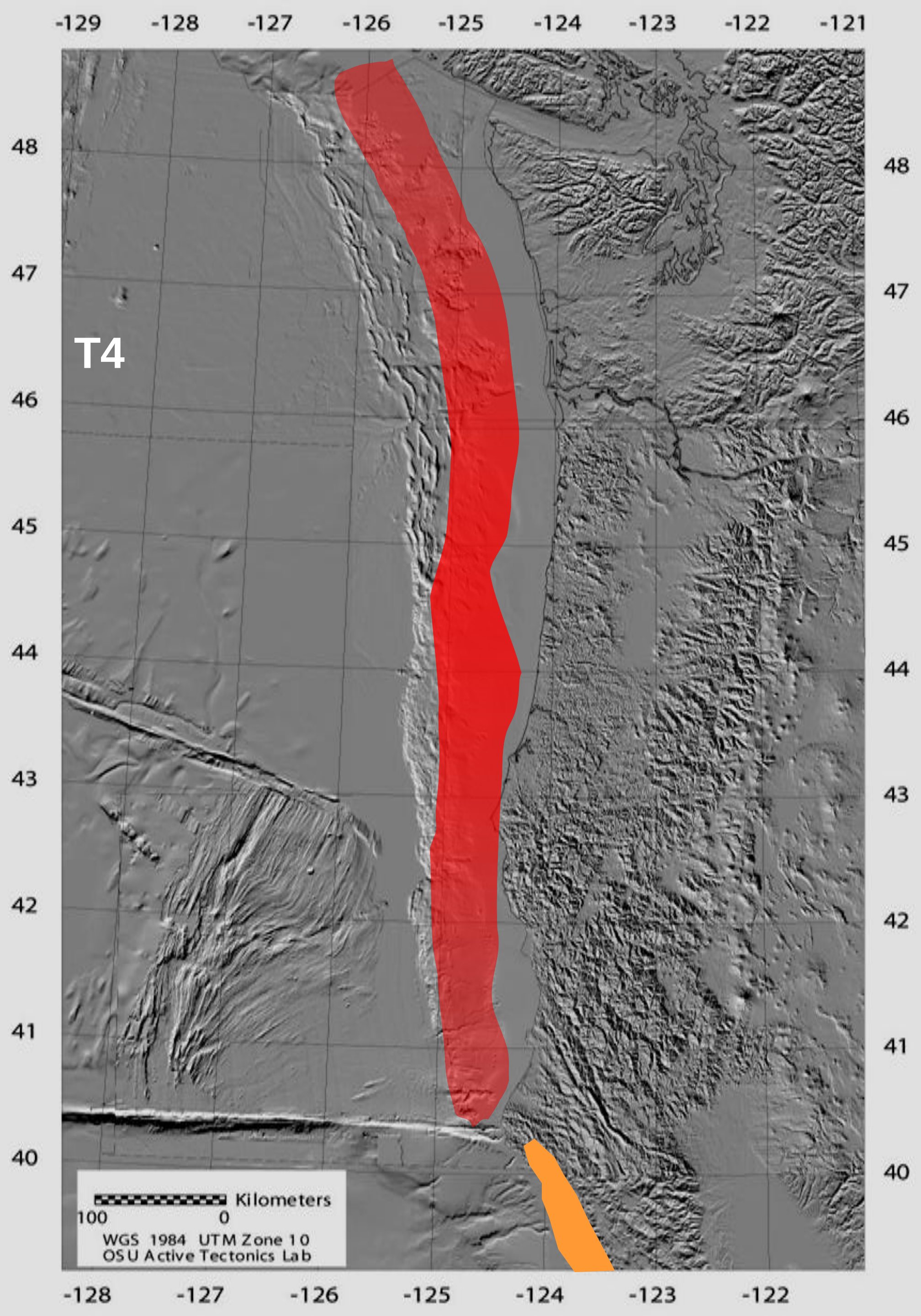


-129 -128 -127 -126 -125 -124 -123 -122 -121
48
47
46
45
44
43
42
41
40
T5a
Kilometers
100 0
WGS 1984 UTM Zone 10
OSU Active Tectonics Lab
-128 -127 -126 -125 -124 -123 -122

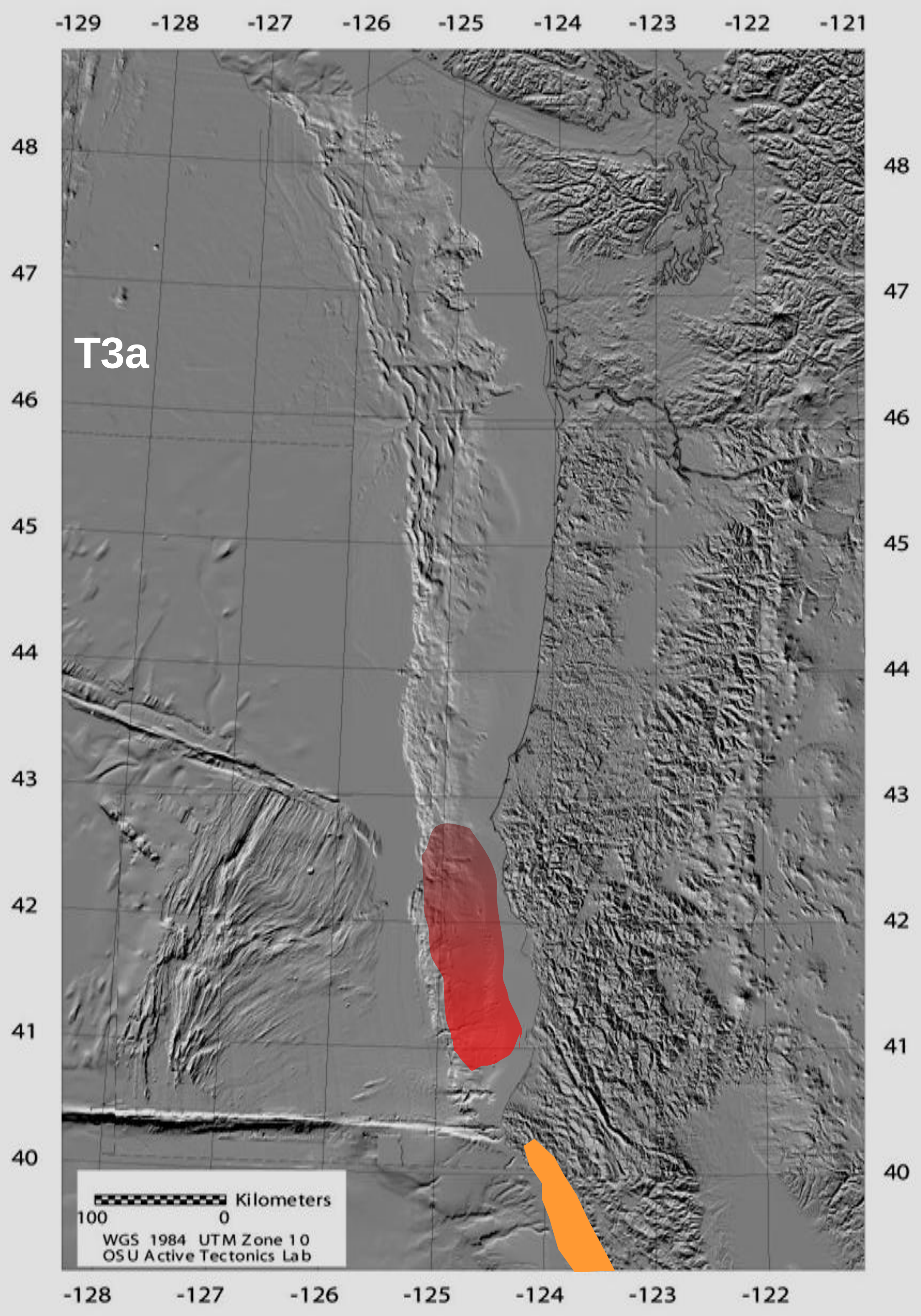


-129 -128 -127 -126 -125 -124 -123 -122 -121
48 47 46 45 44 43 42 41 40
T5
Another
~ 1000 year
Gap (north only)
Ends
~ 1500 BP
Kilometers
100 0
WGS 1984 UTM Zone 10
OSU Active Tectonics Lab
-128 -127 -126 -125 -124 -123 -122

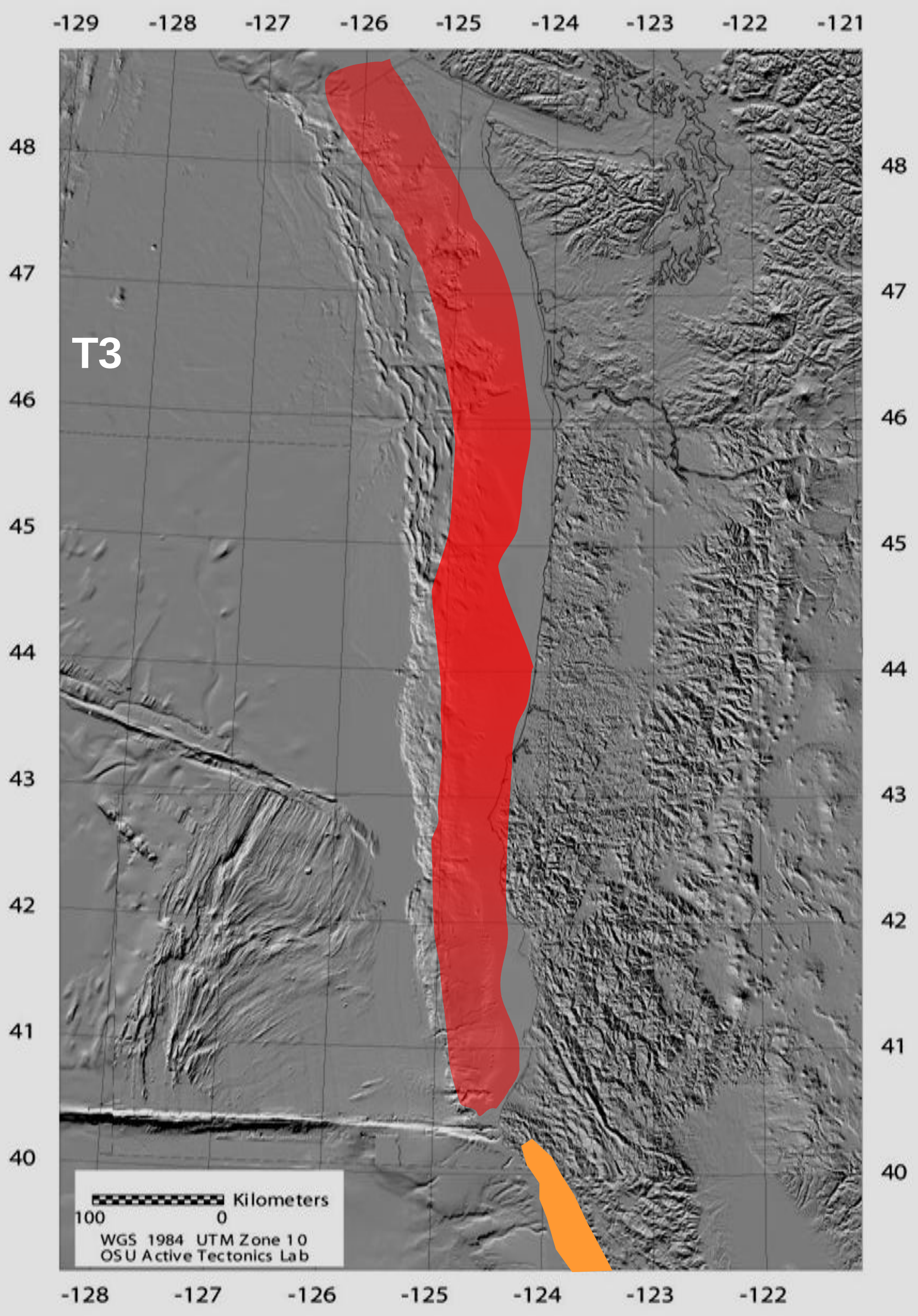

-129
-128
-127
-126
-125
-124
-123
-122
-121
48
47
46
45
44
43
42
41
40
T4a
Kilometers
100
0
WGS 1984 UTM Zone 10
OSU Active Tectonics Lab
-128
-127
-126
-125
-124
-123
-122



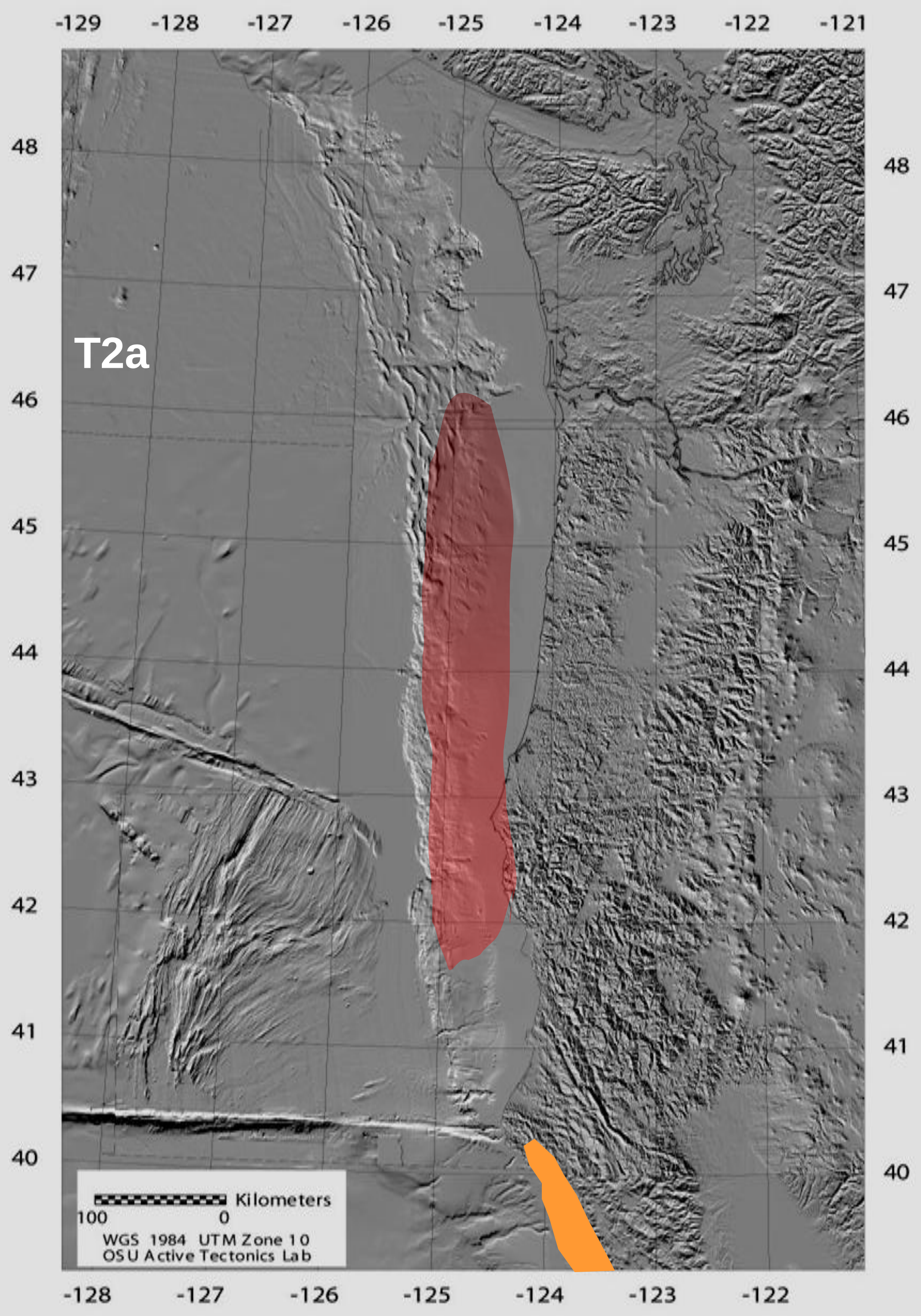
-129 -128 -127 -126 -125 -124 -123 -122 -121
48
47
46
45
44
43
42
41
40
T4
Kilometers
100 0
WGS 1984 UTM Zone 10
OSU Active Tectonics Lab
-128 -127 -126 -125 -124 -123 -122



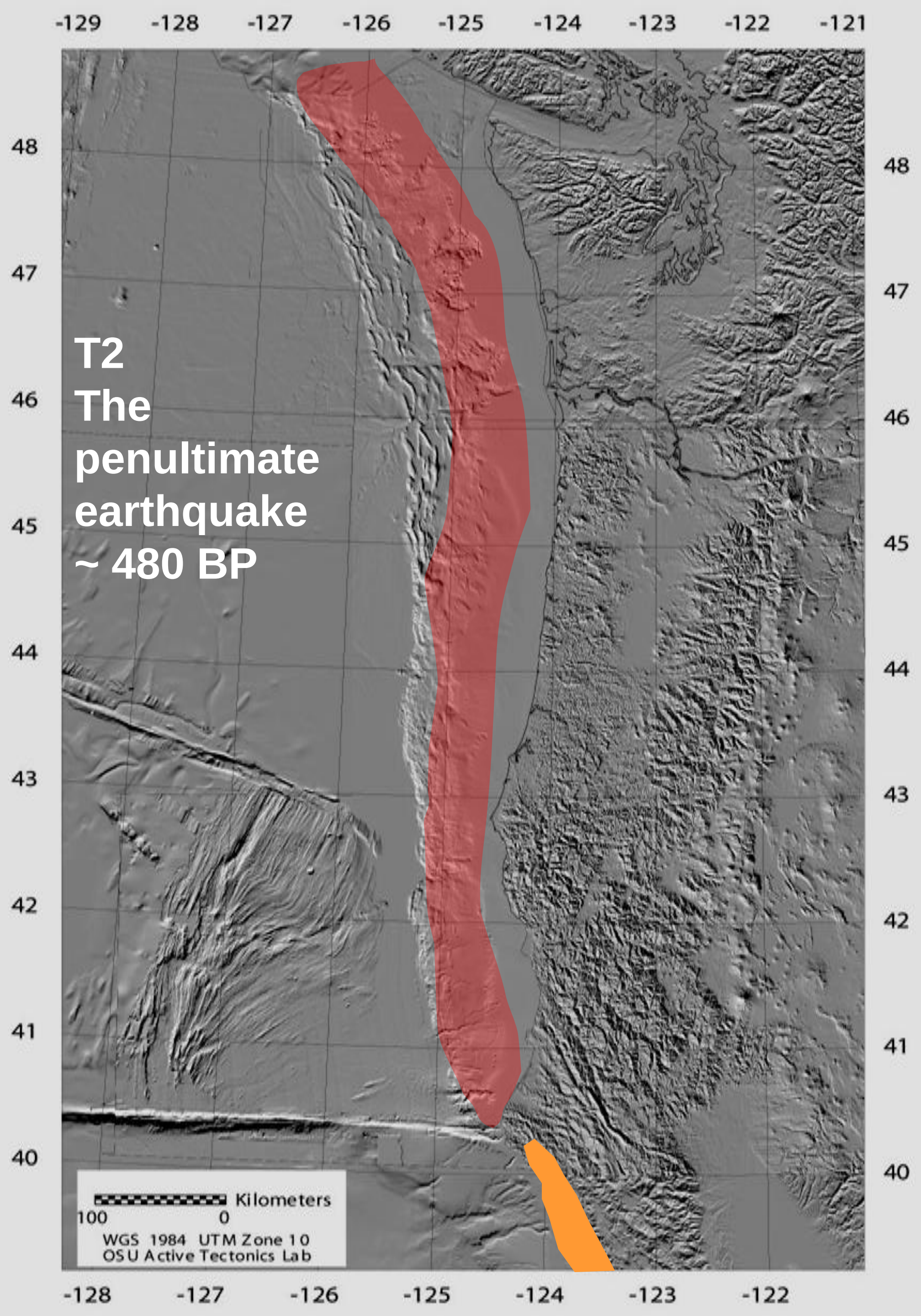
-129 -128 -127 -126 -125 -124 -123 -122 -121
48
47
46
45
44
43
42
41
40
T3a
Kilometers
100 0
WGS 1984 UTM Zone 10
OSU Active Tectonics Lab
-128 -127 -126 -125 -124 -123 -122



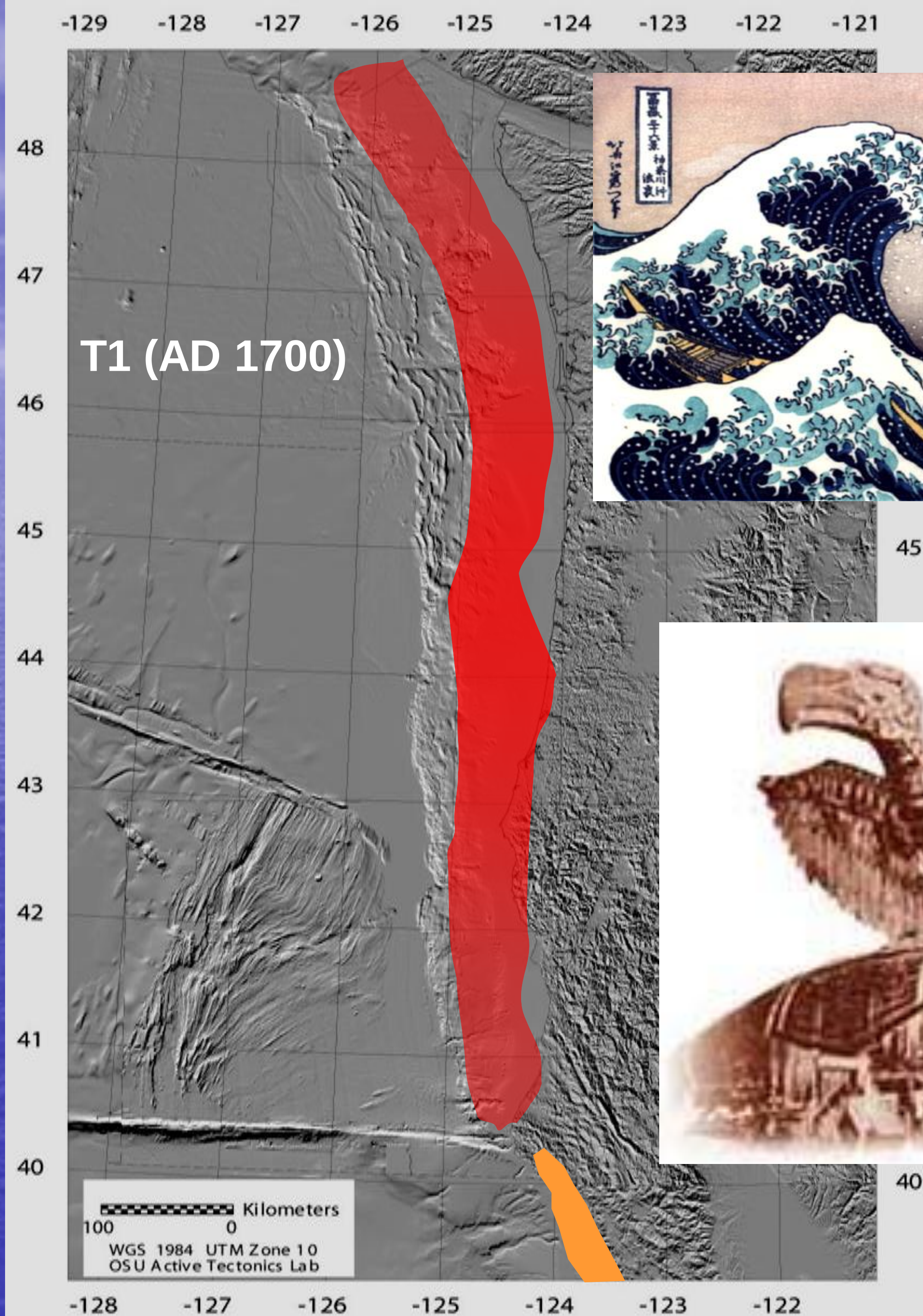
-129 -128 -127 -126 -125 -124 -123 -122 -121
48 47 46 45 44 43 42 41 40
T3
Kilometers
100 0
WGS 1984 UTM Zone 10
OSU Active Tectonics Lab
-128 -127 -126 -125 -124 -123 -122

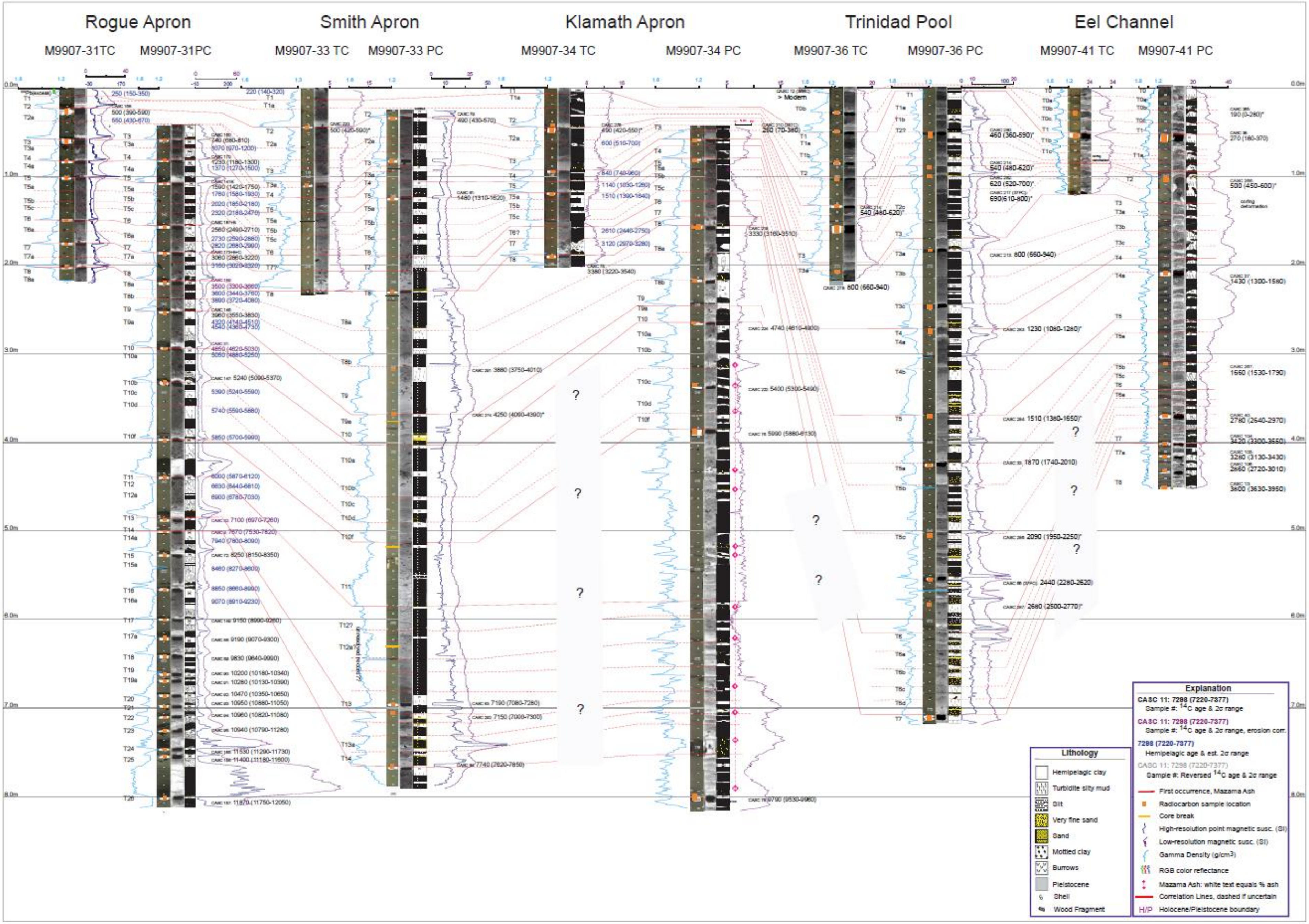


T2a
Kilometers
100
0
WGS 1984 UTM Zone 10
OSU Active Tectonics Lab



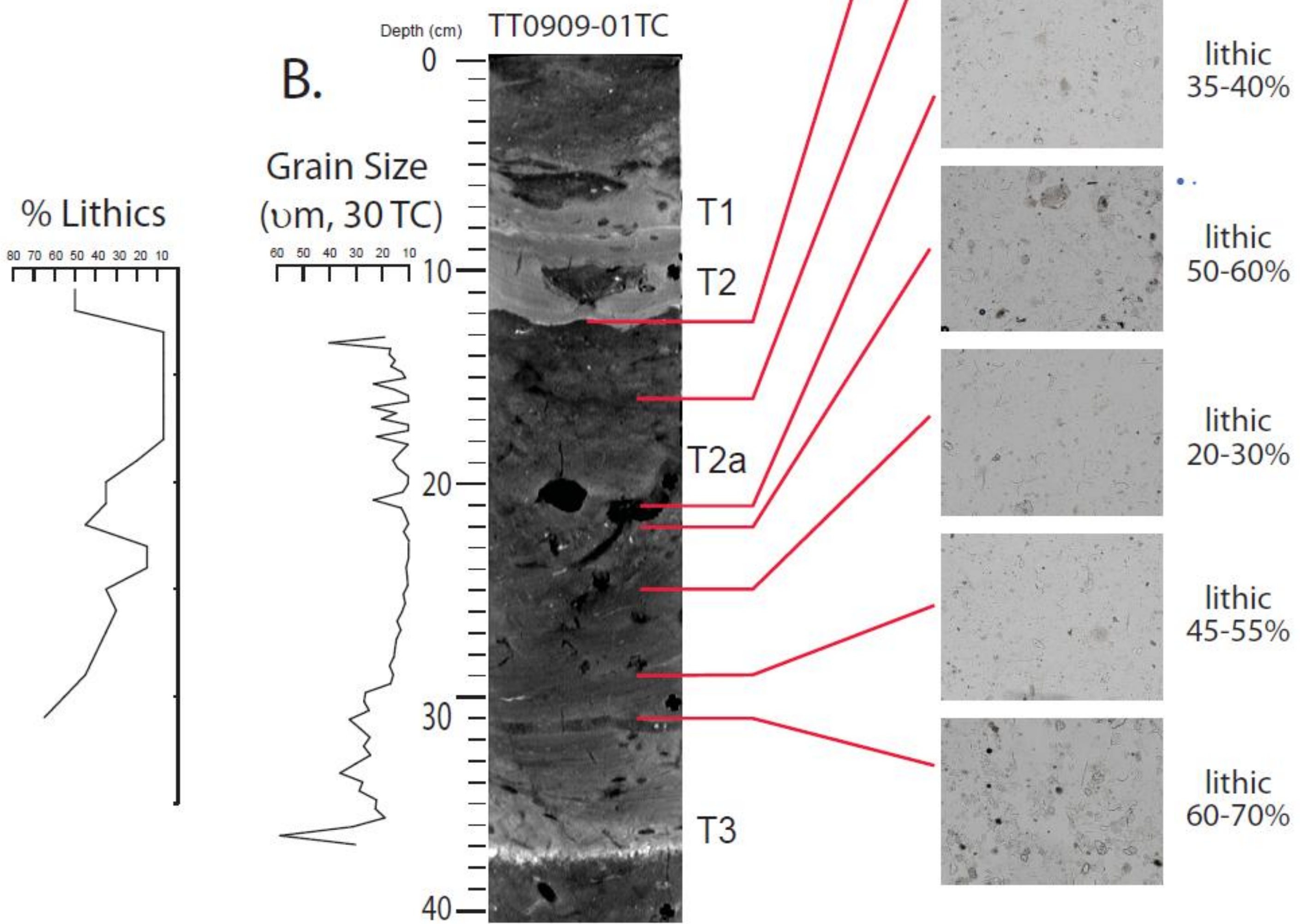
-129
-128
-127
-126
-125
-124
-123
-122
-121
48
47
46
45
44
43
42
41
40
T2
The
penultimate
earthquake
~ 480 BP
Kilometers
100
0
WGS 1984 UTM Zone 10
OSU Active Tectonics Lab

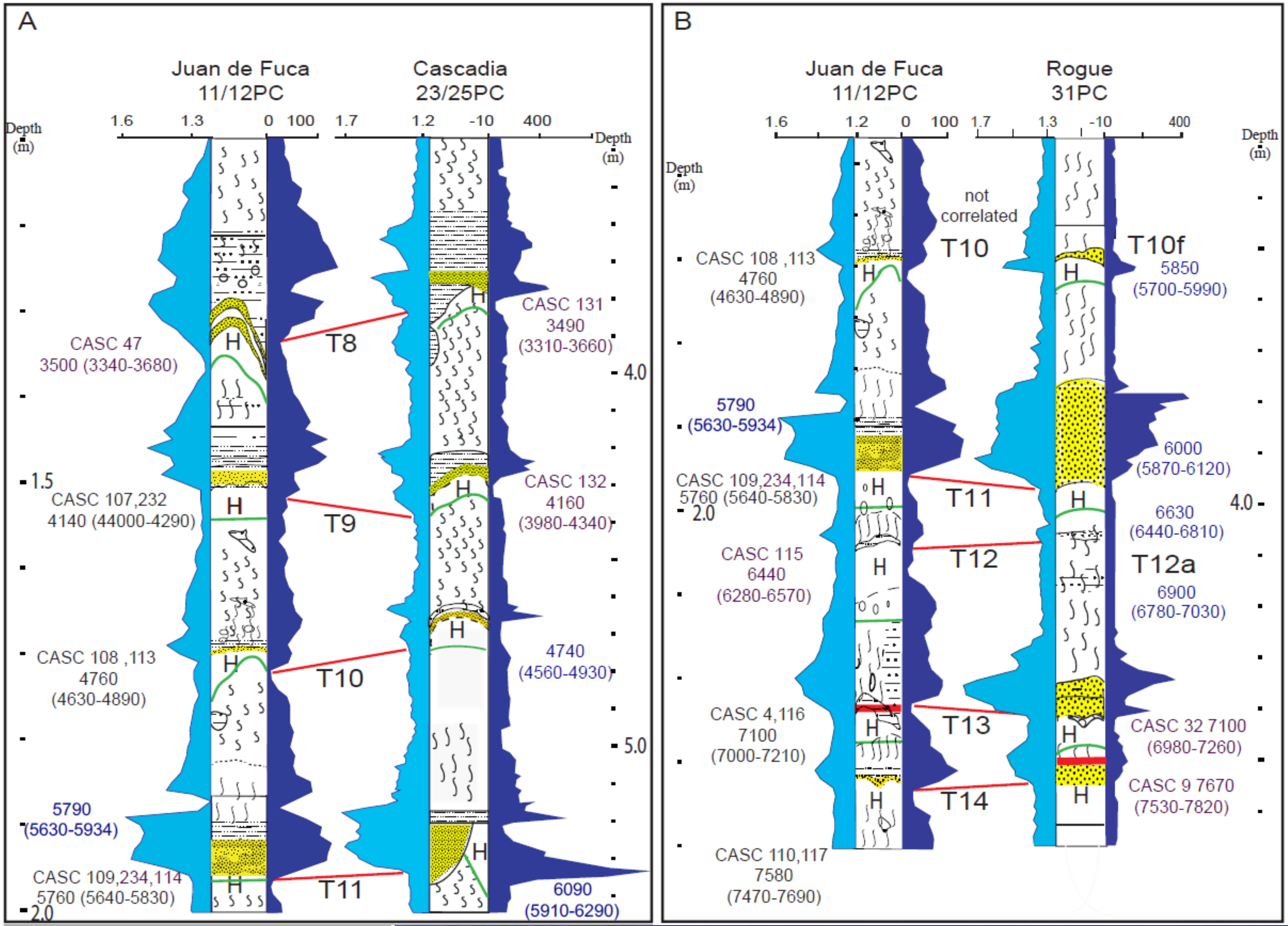

T1 (AD 1700)
-129 -128 -127 -126 -125 -124 -123 -122 -121
48
47
46
45
44
43
42
41
40
Kilometers
100 0
WGS 1984 UTM Zone 10
OSU Active Tectonics Lab
-128 -127 -126 -125 -124 -123 -122

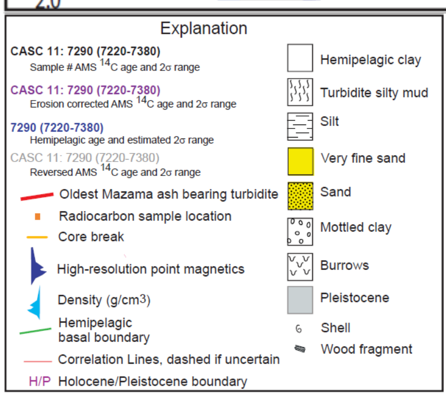


Rogue Apron
M9907-31TC
M9907-31PC
Smith Apron
M9907-33 TC
M9907-33 PC
Klamath Apron
M9907-34 TC
M9907-34 PC
Trinidad Pool
M9907-36 TC
M9907-36 PC
Eel Channel
M9907-41 TC
M9907-41 PC
Lithology
Hemipelagic clay
Turbidite silty mud
Silt
Very fine sand
Sand
Mottled clay
Burrows
Pleistocene
Shell
Wood Fragment
Explanation
Radiocarbon sample location
Core break
High-resolution point magnetic susc. (SI)
Low-resolution magnetic susc. (SI)
RGB color reflectance
Mazama Ash: white text equals % ash
Correlation Lines, dashed if uncertain
H/P Holocene/Pleistocene boundary

This example T2a, is one of the least robust at Rogue Apron. It has a sharp base, but small scale bioturbation has chewed up the base and smeared the coarser material significantly. The same bioturbation and presence of large biogenic fragments makes laser grain size problematic. The most telling trait is the lithic fraction, and presence of intact radiolarians in the interbedded hemipelagic.







Zooming in a bit, here are typical examples of the Holocene sequences.

In this case T10-T14 at Juan de Fuca channel and Cascadia channel are shown.

Part of the correlation matrix includes the vertical pattern of thickness and mass, as well as the vertical sequence of event "pulses".

We are using Gamma density and magnetic susceptibility as proxies for grain size for each depositional sequence.

You can see here the general pattern of similarity, as well as the variability between cores, and between geophysical signatures in the same core.

While considerable variability exists from core to core, with enough cores, a consistent pattern began to emerge. We observed very similar sequences in widely separated locations, suggesting stratigraphic correlation over significant distances was possible, even if there was no physical connection between the sites, or the deposits themselves. Now believe there are more physical connections that we first thought based on high resolution seismic data, but some sites are clearly isolated.